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INTERGOVERNMENTAL PANEL ON climate change

CLIMATE CHANGE 2014

Impacts, Adaptation, and Vulnerability

Part A: Global and Sectoral Aspects

WG II

WORKING GROUP II CONTRIBUTION TO THE FIFTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO UNEP

Climate Change 2014
Impacts, Adaptation, and Vulnerability
Part A: Global and Sectoral Aspects

Working Group II Contribution to the
Fifth Assessment Report of the
Intergovernmental Panel on Climate Change

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Planting of mangrove seedlings in Funafala, Funafuti Atoll, Tuvalu. © David J. Wilson

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Foreword, Preface, and Dedication

Foreword

Climate Change 2014: Impacts, Adaptation, and Vulnerability is the second volume of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) — *Climate Change 2013/2014* — and was prepared by its Working Group II. The volume focuses on why climate change matters and is organized into two parts, devoted respectively to human and natural systems and regional aspects, incorporating results from the reports of Working Groups I and III. The volume addresses impacts that have already occurred and risks of future impacts, especially the way those risks change with the amount of climate change that occurs and with investments in adaptation to climate changes that cannot be avoided. For both past and future impacts, a core focus of the assessment is characterizing knowledge about vulnerability, the characteristics and interactions that make some events devastating, while others pass with little notice.

Three elements are new in this assessment. Each contributes to a richer, more nuanced understanding of climate change in its real-world context. The first new element is a major expansion of the topics covered in the assessment. In moving from 20 chapters in the AR4 to 30 in the AR5, the Working Group II assessment makes it clear that expanding knowledge about climate change and its impacts mandates attention to more sectors, including sectors related to human security, livelihoods, and the oceans. The second new element is a pervasive focus on risk, where risk captures the combination of uncertain outcomes and something of value at stake. A framing based on risk provides a framework for utilizing information on the full range of possible outcomes, including not only most likely outcomes but also low probability but high consequence events. The third new element is solid grounding in the evidence that impacts of climate change typically involve a number of interacting factors, with climate change adding new dimensions and complications. The implication is that understanding the impacts of climate change requires a very broad perspective.

The IPCC was established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) in 1988, with the mandate to provide the world community with the most up-to-date and comprehensive scientific, technical, and socio-economic information about climate change. The IPCC assessments have since then played a major role in motivating governments to adopt and implement policies in responding to climate change, including the United Nations Framework Convention on Climate Change and the Kyoto Protocol. IPCC's AR5 provides an important foundation of information for the world's policymakers, to help them respond to the challenge of climate change.

The *Impacts, Adaptation, and Vulnerability* report was made possible thanks to the commitment and voluntary labor of a large number of leading scientists. We would like to express our gratitude to all Coordinating Lead Authors, Lead Authors, Contributing Authors, Review Editors, and Reviewers. We would also like to thank the staff of the Working Group II Technical Support Unit and the IPCC Secretariat for their dedication in organizing the production of a very successful IPCC report. Furthermore, we would like to express our thanks to Dr. Rajendra K. Pachauri, Chairman of the IPCC, for his patient and constant guidance through the process, and to Drs. Vicente Barros and Chris Field, Co-Chairs of Working Group II, for their skillful leadership. We also wish to acknowledge and thank those governments and institutions that contributed to the IPCC Trust Fund and supported the participation of their resident scientists in the IPCC process. We would like to mention in particular the Government of the United States of America, which funded the Technical Support Unit; the Government of Japan, which hosted the plenary session for the approval of the report; and the Governments of Japan, United States of America, Argentina, and Slovenia, which hosted the drafting sessions to prepare the report.

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Preface

The Working Group II contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC WGII AR5) considers climate change impacts, adaptation, and vulnerability. It provides a comprehensive, up-to-date picture of the current state of knowledge and level of certainty, based on the available scientific, technical, and socio-economic literature. As with all IPCC products, the report is the result of an assessment process designed to highlight both big-picture messages and key details, to integrate knowledge from diverse disciplines, to evaluate the strength of evidence underlying findings, and to identify topics where understanding is incomplete. The focus of the assessment is providing information to support good decisions by stakeholders at all levels. The assessment is a unique source of background for decision support, while scrupulously avoiding advocacy for particular policy options.

Scope of the Report

Climate change impacts, adaptation, and vulnerability span a vast range of topics. With the deepening of knowledge about climate change, we see connections in expanding and diverse areas, activities, and assets at risk. Early research focused on direct impacts of temperature and rainfall on humans, crops, and wild plants and animals. New evidence points to the importance of understanding not only these direct impacts but also potential indirect impacts, including impacts that can be transmitted around the world through trade, travel, and security. As a consequence, few aspects of the human endeavor or of natural ecosystem processes are isolated from possible impacts in a changing climate. The interconnectedness of the Earth system makes it impossible to draw a confined boundary around climate change impacts, adaptation, and vulnerability. This report does not attempt to bound the issue. Instead, it focuses on core elements and identifies connecting points where the issue of climate change overlaps with or merges into other issues.

The integrative nature of the climate change issue underlies three major new elements of the WGII contribution to the AR5. The first is explicit coverage of a larger range of topics, with new chapters. Increasing knowledge, expressed in a rapidly growing corpus of published literature, enables deeper assessment in a number of areas. Some of these are geographic, especially the addition of two chapters on oceans. Other new chapters further develop topics covered in earlier assessments, reflecting the increased sophistication of the available research. Expanded coverage of human settlements, security, and livelihoods builds on new research concerning human dimensions of climate change. A large increase in the published literature on adaptation motivates assessment in a suite of chapters.

A second new emphasis is the focus on climate change as a challenge in managing and reducing risk, as well as capitalizing on opportunities. There are several advantages to understanding the risk of impacts from climate change as resulting from the overlap of hazards from the physical climate and the vulnerability and exposure of people, ecosystems, and assets. Some of the advantages accrue from the opportunity to evaluate factors that regulate each component of risk. Others relate to the way that a focus on risk can clarify bridges to solutions. A focus on risk can link historical experience with future projections. It helps integrate the role of extremes. And it highlights the importance of considering the full range of possible outcomes, while opening the door to a range of tools relevant to decision making under uncertainty.

A third new emphasis ties together the interconnectedness of climate change with a focus on risk. Risks of climate change unfold in environments with many interacting processes and stressors. Often, climate change acts mainly through adding new dimensions and complications to sometimes longstanding challenges. Appreciating the multi-stressor context of the risks of climate change can open doors to new insights and approaches for solutions.

Increased knowledge of the risks of climate change can be a starting point for understanding the opportunities for and implications of possible solutions. Some of the solution space is in the domain of mitigation, extensively covered by the Working Group III contribution to the AR5. The WGII AR5 delves deep into adaptation. But many opportunities exist in linking climate change adaptation, mitigation, and sustainable development. In contrast to past literature that tended to characterize adaptation, mitigation, and sustainable development as competing agendas, new literature identifies complementarities. It shines light on options for leveraging investments in managing and reducing the risks of climate change to enable vibrant communities, robust economies, and healthy ecosystems, in all parts of the world.

Structure of the Report

The Working Group II contribution to the IPCC Fifth Assessment Report consists of a brief summary for policymakers, a longer technical summary, and 30 thematic chapters, plus supporting annexes. A series of cross-chapter boxes and a collection of Frequently Asked Questions provide an integrated perspective on selected key issues. Electronic versions of all the printed contents, plus supplemental online material, are available at no charge at www.ipcc.ch.

The report is published in two parts. Part A covers global-scale topics for a wide range of sectors, covering physical, biological, and human systems. Part B considers the same topics, but from a regional perspective, exploring the issues that arise from the juxtaposition of climate change, environment, and available resources. Conceptually, there is some overlap between the material in Parts A and B, but the contrast in framing makes each part uniquely relevant to a particular group of stakeholders. For setting context and meeting the needs of users focused on regional-scale issues, Part B extracts selected materials from the Working Group I and Working Group III contributions to the Fifth Assessment Report. To acknowledge the different purposes for the two parts and the balanced contributions of the co-chairs, the listing order of the editors differs between the two parts, with Chris Field listed first on Part A and Vicente Barros listed first on Part B.

The 20 chapters in Part A are arranged in six thematic groups.

Context for the AR5

The two chapters in this group, (1) Point of departure and (2) Foundations for decision making, briefly summarize the conclusions of the Fourth Assessment Report and the Working Group I contribution to the AR5. They explain the motivation for the focus on climate change as a challenge in managing and reducing risks and assess the relevance of diverse approaches to decision making in the context of climate change.

Natural and Managed Resources and Systems, and Their Uses

The five chapters in this group, (3) Freshwater resources, (4) Terrestrial and inland water systems, (5) Coastal systems and low-lying areas, (6) Ocean systems, and (7) Food security and food production systems, cover diverse sectors, with a new emphasis on resource security. The ocean systems chapter, focused on the processes at work in ocean ecosystems, is a major element of the increased coverage of oceans in the WGII AR5.

Human Settlements, Industry, and Infrastructure

The three chapters in this group, (8) Urban areas, (9) Rural areas, and (10) Key economic sectors and services, provide expanded coverage of settlements and economic activity. With so many people living in and moving to cities, urban areas are increasingly important in understanding the climate change issue.

Human Health, Well-Being, and Security

The three chapters in this group, (11) Human health: impacts, adaptation, and co-benefits, (12) Human security, and (13) Livelihoods and poverty, increase the focus on people. These chapters address a wide range of processes, from vector-borne disease through conflict and migration. They assess the relevance of local and traditional knowledge.

Adaptation

An expanded treatment of adaptation is one of the signature changes in the WGII AR5. Chapters treat (14) Adaptation needs and options, (15) Adaption planning and implementation, (16) Adaptation opportunities, constraints, and limits, and (17) Economics of adaptation. This coverage reflects a large increase in literature and the emergence of climate-change adaptation plans in many countries and concrete action in some.

Multi-Sector Impacts, Risks, Vulnerabilities, and Opportunities

The three chapters in this group, (18) Detection and attribution of observed impacts, (19) Emergent risks and key vulnerabilities, and (20) Climate-resilient pathways: adaptation, mitigation, and sustainable development, collect material from the chapters in both Parts A and B to provide a sharp focus on aspects of climate change that emerge only by examining many examples across the regions of the Earth and the entirety of the human endeavor. These chapters provide an integrative view of three central questions related to understanding risks in a changing climate – what are the impacts to date (and how certain is the link to climate change), what are the most important risks looking forward, and what are the opportunities for linking responses to climate change with other societal goals.

The 10 chapters in Part B start with a chapter, (21) Regional context, structured to help readers understand and capitalize on regional information. It is followed by chapters on 9 world regions: (22) Africa, (23) Europe, (24) Asia, (25) Australasia, (26) North America, (27) Central and South America, (28) Polar regions, (29) Small islands, and (30) The ocean (taking a regional cut through ocean issues, including human utilization of ocean resources). Each chapter in this part is an all-in-one resource for regional stakeholders, while also contributing to and building from the global assessment. Regional climate-change maps, which complement the Working Group I Atlas of Global and Regional Climate Projections, and quantified key regional risks are highlights of these chapters. Each chapter explores the issues and themes that are most relevant in the region.

Process

The Working Group II contribution to the IPCC Fifth Assessment Report was prepared in accordance with the procedures of the IPCC. Chapter outlines were discussed and defined at a scoping meeting in Venice in July 2009, and outlines for the three Working Group contributions were approved at the 31st session of the Panel in November 2009, in Bali, Indonesia. Governments and IPCC observer organizations nominated experts for the author team. The team of 64 Coordinating Lead Authors, 179 Lead Authors, and 66 Review Editors was selected by the WGII Bureau and accepted by the IPCC Bureau in May 2010. More than 400 Contributing Authors, selected by the chapter author teams, contributed text.

Drafts prepared by the author teams were submitted for two rounds of formal review by experts, of which one was also a review by governments. Author teams revised the draft chapters after each round of review, with Review Editors working to assure that every review comment was fully considered, and where appropriate, chapters were adjusted to reflect points raised in the reviews. In addition, governments participated in a final round of review of the draft Summary for Policymakers. All of the chapter drafts, review comments, and author responses are available online via www.ipcc.ch. Across all of the drafts, the WGII contribution to the AR5 received 50,492 comments from 1,729 individual expert reviewers from 84 countries. The Summary for Policymakers was approved line-by-line by the Panel, and the underlying chapters were accepted at the 10th Session of IPCC Working Group II and the 38th Session of the IPCC Panel, meeting in Yokohama, Japan, from March 25-30, 2014.

Acknowledgments

For the AR5, Working Group II had an amazing author team. In many ways, the author team encompasses the entire scientific community, including scientists who conducted the research and wrote the research papers on which the assessment is based, and the reviewers who contributed their wisdom in more than 50,000 review comments. But the process really ran on the sophistication, wisdom, and dedication of the 309 individuals from 70 countries who comprise the WGII team of Coordinating Lead Authors, Lead Authors, and Review Editors. These individuals, with the support of a talented group of volunteer chapter scientists and the assistance of scores of contributing authors, demonstrated an inspirational commitment to scientific quality and public service. Tragically, three of our most experienced authors passed away while the report was being written. We greatly miss JoAnn Carmin, Abby Sallenger, and Steve Schneider.

We benefitted greatly from the advice and guidance of the Working Group II Bureau: Amjad Abdulla (Maldives), Eduardo Calvo Buendía (Peru), José M. Moreno (Spain), Nirivololona Raholijao (Madagascar), Sergey Semenov (Russian Federation), and Neville Smith (Australia). Their understanding of regional resources and concerns has been invaluable.

Throughout the AR5, we benefitted greatly from the wisdom and insight of our colleagues in the IPCC leadership, especially the IPCC chair, R.K. Pachauri. All of the members of the IPCC Executive Committee worked effectively and selflessly on issues related to the reports from all three working groups. We extend a heartfelt thanks to all of the members of the ExCom: R.K. Pachauri, Ottmar Edenhofer, Ismail El Gizouli, Taka Hiraishi, Thelma Krug, Hoesung Lee, Ramón Pichs Madruga, Qin Dahe, Youba Sokona, Thomas Stocker, and Jean-Pascal van Ypersele.

We are very appreciative of the enthusiastic cooperation of the nations that hosted our excellent working meetings, including four lead author meetings and the 10th Session of Working Group II. We gratefully acknowledge the support of the governments of Japan, the United States, Argentina, and Slovenia for hosting the lead author meetings, and the government of Japan for hosting the approval session. The government of the United States provided essential financial support for the Working Group II Technical Support Unit. Special thanks to the principals of the United States Global Change Research Program for orchestrating the funding across many research agencies.

We want very much to thank the staff of the IPCC Secretariat: Renate Christ, Gaetano Leone, Carlos Martin-Novella, Jonathan Lynn, Brenda Abrar-Milani, Jesbin Baidya, Laura Biagioni, Mary Jean Burer, Annie Courtin, Judith Ewa, Joelle Fernandez, Nina Peeva, Sophie Schlingemann, Amy Smith, and Werani Zabula. Thanks to Francis Hayes who served as conference officer for the approval session. Thanks to the individuals who coordinated the organization for each of the lead authors meetings. This was Mizue Yuzurihara and Claire Summers for LAM1, Sandy MacCracken for LAM2, Ramiro Saurral for LAM3, and Mojca Deželak for LAM4. Students from Japan, the United States, Argentina, and Slovenia helped with the lead author meetings.

The WGII Technical Support Unit was fabulous. They combined scientific sophistication, technical excellence, artistic vision, deep resilience, and profound dedication, not to mention a marked ability to compensate for oversights by and deficiencies of the co-chairs. Dave Dokken, Mike Mastrandrea, Katie Mach, Kris Ebi, Monalisa Chatterjee, Sandy MacCracken, Eric Kissel, Yuka Estrada, Leslie White, Eren Bilir, Rob Genova, Beti Girma, Andrew Levy, and Patricia Mastrandrea have all made wonderful contributions to the report. In addition, the work of David Ropeik (frequently asked questions), Marcos Senet (assistant to Vicente Barros), Terry Kornak (technical edits), Marilyn Anderson (index), Liu Yingjie (Chinese author support), and Janak Pathak (UNEP communications) made a big difference. Kyle Terran, Gete Bond, and Sandi Fikes facilitated travel. Volunteer contributions from John Kelley and Ambarish Malpani greatly enhanced reference management. Catherine Lemmi, Ian Sparkman, and Danielle Olivera were super interns.

We extend a deep, personal thanks to our families and to the families of every author and reviewer. We know you tolerated many late nights and weekends with partners, parents, or children sitting at the computer or mumbling about one more assignment from us.

Vicente Barros
IPCC WGII Co-Chair

Chris Field
IPCC WGII Co-Chair

Dedication


Credit: Odd-Steinar Tøllefsen

Yuri Antonievich Izrael
(15 May 1930 to 23 January 2014)

The Working Group II contribution to the IPCC Fifth Assessment Report is dedicated to the memory of Professor Yuri Antonievich Izrael, first Chair of Working Group II from 1988 to 1992 and IPCC Vice Chair from 1992 to 2008. Professor Izrael was a pioneer, opening doors that have allowed thousands of scientists to contribute to the work of the IPCC.

Through a long and distinguished career, Professor Izrael was a strong proponent of environmental sciences, meteorology, climatology, and international organizations, especially the IPCC and the World Meteorological Organization. A creative researcher and tireless institution builder, Dr. Izrael founded and for more than two decades led the Institute of Global Climate and Ecology.

In the IPCC, Professor Izrael played a central role in creating the balance of IPCC efforts on careful observations, mechanisms, and systematic projections using scenarios. An outspoken advocate for the robust integration of scientific excellence and broad participation in IPCC reports, Dr. Izrael pioneered many of the features that assure the comprehensiveness and integrity of IPCC reports.

Summary for Policymakers

SPM

Summary for Policymakers

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ASSESSING AND MANAGING THE RISKS OF CLIMATE CHANGE

Human interference with the climate system is occurring,[1] and climate change poses risks for human and natural systems (Figure SPM.1). The assessment of impacts, adaptation, and vulnerability in the Working Group II contribution to the IPCC's Fifth Assessment Report (WGII AR5) evaluates how patterns of risks and potential benefits are shifting due to climate change. It considers how impacts and risks related to climate change can be reduced and managed through adaptation and mitigation. The report assesses needs, options, opportunities, constraints, resilience, limits, and other aspects associated with adaptation.

Climate change involves complex interactions and changing likelihoods of diverse impacts. A focus on risk, which is new in this report, supports decision making in the context of climate change and complements other elements of the report. People and societies may perceive or rank risks and potential benefits differently, given diverse values and goals.

Compared to past WGII reports, the WGII AR5 assesses a substantially larger knowledge base of relevant scientific, technical, and socioeconomic literature. Increased literature has facilitated comprehensive assessment across a broader set of topics and sectors, with expanded coverage of human systems, adaptation, and the ocean. See Background Box SPM.1.[2]

Section A of this summary characterizes observed impacts, vulnerability and exposure, and adaptive responses to date. Section B examines future risks and potential benefits. Section C considers principles for effective adaptation and the broader interactions among adaptation, mitigation,

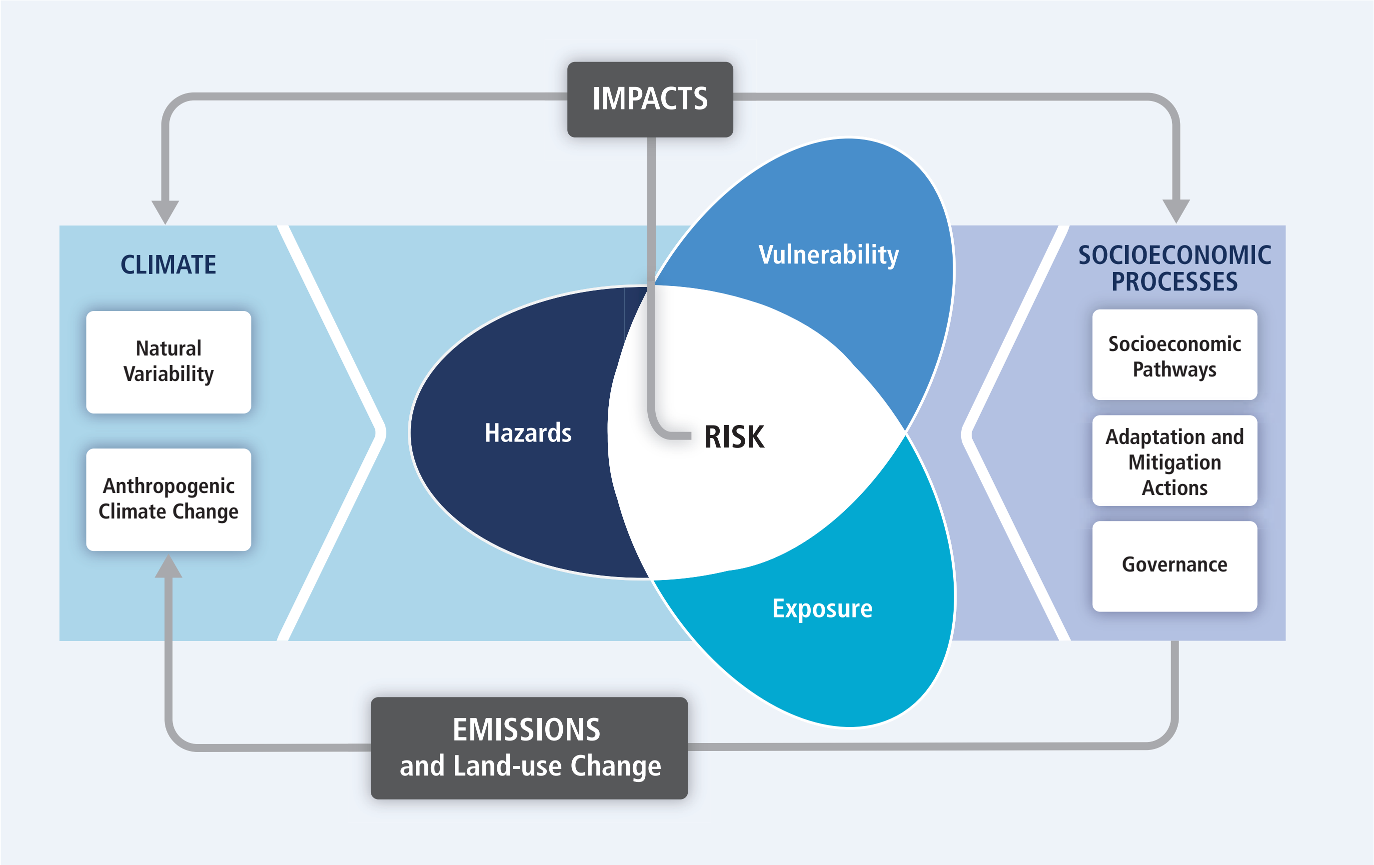

Figure SPM.1 | Illustration of the core concepts of the WGII AR5. Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. Changes in both the climate system (left) and socioeconomic processes including adaptation and mitigation (right) are drivers of hazards, exposure, and vulnerability. [19.2, Figure 19-1]

[1] A key finding of the WGI AR5 is, "It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century." [WGI AR5 SPM Section D.3, 2.2, 6.3, 10.3-6, 10.9]

[2] 1.1, Figure 1-1

Background Box SPM.1 | Context for the Assessment

For the past 2 decades, IPCC's Working Group II has developed assessments of climate-change impacts, adaptation, and vulnerability. The WGII AR5 builds from the WGII contribution to the IPCC's Fourth Assessment Report (WGII AR4), published in 2007, and the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX), published in 2012. It follows the Working Group I contribution to the AR5 (WGI AR5).[3]

The number of scientific publications available for assessing climate-change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, with especially rapid increases in publications related to adaptation. Authorship of climate-change publications from developing countries has increased, although it still represents a small fraction of the total.[4]

The WGII AR5 is presented in two parts (Part A: Global and Sectoral Aspects, and Part B: Regional Aspects), reflecting the expanded literature basis and multidisciplinary approach, increased focus on societal impacts and responses, and continued regionally comprehensive coverage.

and sustainable development. Background Box SPM.2 defines central concepts, and Background Box SPM.3 introduces terms used to convey the degree of certainty in key findings. Chapter references in brackets and in footnotes indicate support for findings, figures, and tables.

A: OBSERVED IMPACTS, VULNERABILITY, AND ADAPTATION IN A COMPLEX AND CHANGING WORLD

A-1. Observed Impacts, Vulnerability, and Exposure

In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Evidence of climate-change impacts is strongest and most comprehensive for natural systems. Some impacts on human systems have also been attributed[5] to climate change, with a major or minor contribution of climate change distinguishable from other influences. See Figure SPM.2. Attribution of observed impacts in the WGII AR5 generally links responses of natural and human systems to observed climate change, regardless of its cause.[6]

In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (*medium confidence*). Glaciers continue to shrink almost worldwide due to climate change (*high confidence*), affecting runoff and water resources downstream (*medium confidence*). Climate change is causing permafrost warming and thawing in high-latitude regions and in high-elevation regions (*high confidence*).[7]

Many terrestrial, freshwater, and marine species have shifted their geographic ranges, seasonal activities, migration patterns, abundances, and species interactions in response to ongoing climate change (*high confidence*). See Figure SPM.2B. While only a few recent species extinctions have been attributed as yet to climate change (*high confidence*), natural global climate change at rates slower than current anthropogenic climate change caused significant ecosystem shifts and species extinctions during the past millions of years (*high confidence*).[8]

Based on many studies covering a wide range of regions and crops, negative impacts of climate change on crop yields have been more common than positive impacts (*high confidence*). The smaller number of studies showing positive impacts relate mainly to

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3 1.2-3

4 1.1, Figure 1-1

5 The term *attribution* is used differently in WGI and WGII. Attribution in WGII considers the links between impacts on natural and human systems and observed climate change, regardless of its cause. By comparison, attribution in WGI quantifies the links between observed climate change and human activity, as well as other external climate drivers.

6 18.1, 18.3-6

7 3.2, 4.3, 18.3, 18.5, 24.4, 26.2, 28.2, Tables 3-1 and 25-1, Figures 18-2 and 26-1

8 4.2-4, 5.3-4, 6.1, 6.3-4, 18.3, 18.5, 22.3, 24.4, 25.6, 28.2, 30.4-5, Boxes 4-2, 4-3, 25-3, CC-CR, and CC-MB

Background Box SPM.2 | Terms Central for Understanding the Summary[9]

Climate change: Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

Hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term *hazard* usually refers to climate-related physical events or trends or their physical impacts.

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Impacts: Effects on natural and human systems. In this report, the term *impacts* is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as *consequences* and *outcomes*. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.

Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard (see Figure SPM.1). In this report, the term *risk* is used primarily to refer to the risks of climate-change impacts.

Adaptation: The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Transformation: A change in the fundamental attributes of natural and human systems. Within this summary, transformation could reflect strengthened, altered, or aligned paradigms, goals, or values towards promoting adaptation for sustainable development, including poverty reduction.

Resilience: The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.

high-latitude regions, though it is not yet clear whether the balance of impacts has been negative or positive in these regions (*high confidence*). Climate change has negatively affected wheat and maize yields for many regions and in the global aggregate (*medium confidence*). Effects on rice and soybean yield have been smaller in major production regions and globally, with a median change of zero across all available data, which are fewer for soy compared to the other crops. Observed impacts relate mainly to production aspects of food security rather than access

[9] The WGII AR5 glossary defines many terms used across chapters of the report. Reflecting progress in science, some definitions differ in breadth and focus from the definitions used in the AR4 and other IPCC reports.

SPM

Background Box SPM.3 | Communication of the Degree of Certainty in Assessment Findings[10]

The degree of certainty in each key finding of the assessment is based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement. The summary terms to describe evidence are: *limited*, *medium*, or *robust*; and agreement: *low*, *medium*, or *high*.

Confidence in the validity of a finding synthesizes the evaluation of evidence and agreement. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*.

The likelihood, or probability, of some well-defined outcome having occurred or occurring in the future can be described quantitatively through the following terms: *virtually certain*, 99–100% probability; *extremely likely*, 95–100%; *very likely*, 90–100%; *likely*, 66–100%; *more likely than not*, >50–100%; *about as likely as not*, 33–66%; *unlikely*, 0–33%; *very unlikely*, 0–10%; *extremely unlikely*, 0–5%; and *exceptionally unlikely*, 0–1%. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high confidence*. Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers.

Within paragraphs of this summary, the confidence, evidence, and agreement terms given for a bold key finding apply to subsequent statements in the paragraph, unless additional terms are provided.

or other components of food security. See Figure SPM.2C. Since AR4, several periods of rapid food and cereal price increases following climate extremes in key producing regions indicate a sensitivity of current markets to climate extremes among other factors (*medium confidence*).[11]

At present the worldwide burden of human ill-health from climate change is relatively small compared with effects of other stressors and is not well quantified. However, there has been increased heat-related mortality and decreased cold-related mortality in some regions as a result of warming (*medium confidence*). Local changes in temperature and rainfall have altered the distribution of some water-borne illnesses and disease vectors (*medium confidence*).[12]

Differences in vulnerability and exposure arise from non-climatic factors and from multidimensional inequalities often produced by uneven development processes (*very high confidence*). These differences shape differential risks from climate change. See Figure SPM.1. People who are socially, economically, culturally, politically, institutionally, or otherwise marginalized are especially vulnerable to climate change and also to some adaptation and mitigation responses (*medium evidence*, *high agreement*). This heightened vulnerability is rarely due to a single cause. Rather, it is the product of intersecting social processes that result in inequalities in socioeconomic status and income, as well as in exposure. Such social processes include, for example, discrimination on the basis of gender, class, ethnicity, age, and (dis)ability.[13]

Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability (*very high confidence*). Impacts of such climate-related extremes include alteration of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, morbidity and mortality, and consequences for mental health and human well-being. For countries at all levels of development, these impacts are consistent with a significant lack of preparedness for current climate variability in some sectors.[14]

Climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty (*high confidence*). Climate-related hazards affect poor people's lives directly through impacts on livelihoods, reductions in crop

[10] 1.1, Box 1-1
[11] 7.2, 18.4, 22.3, 26.5, Figures 7-2, 7-3, and 7-7
[12] 11.4-6, 18.4, 25.8
[13] 8.1-2, 9.3-4, 10.9, 11.1, 11.3-5, 12.2-5, 13.1-3, 14.1-3, 18.4, 19.6, 23.5, 25.8, 26.6, 26.8, 28.4, Box CC-GC
[14] 3.2, 4.2-3, 8.1, 9.3, 10.7, 11.3, 11.7, 13.2, 14.1, 18.6, 22.3, 25.6-8, 26.6-7, 30.5, Tables 18-3 and 23-1, Figure 26-2, Boxes 4-3, 4-4, 25-5, 25-6, 25-8, and CC-CR

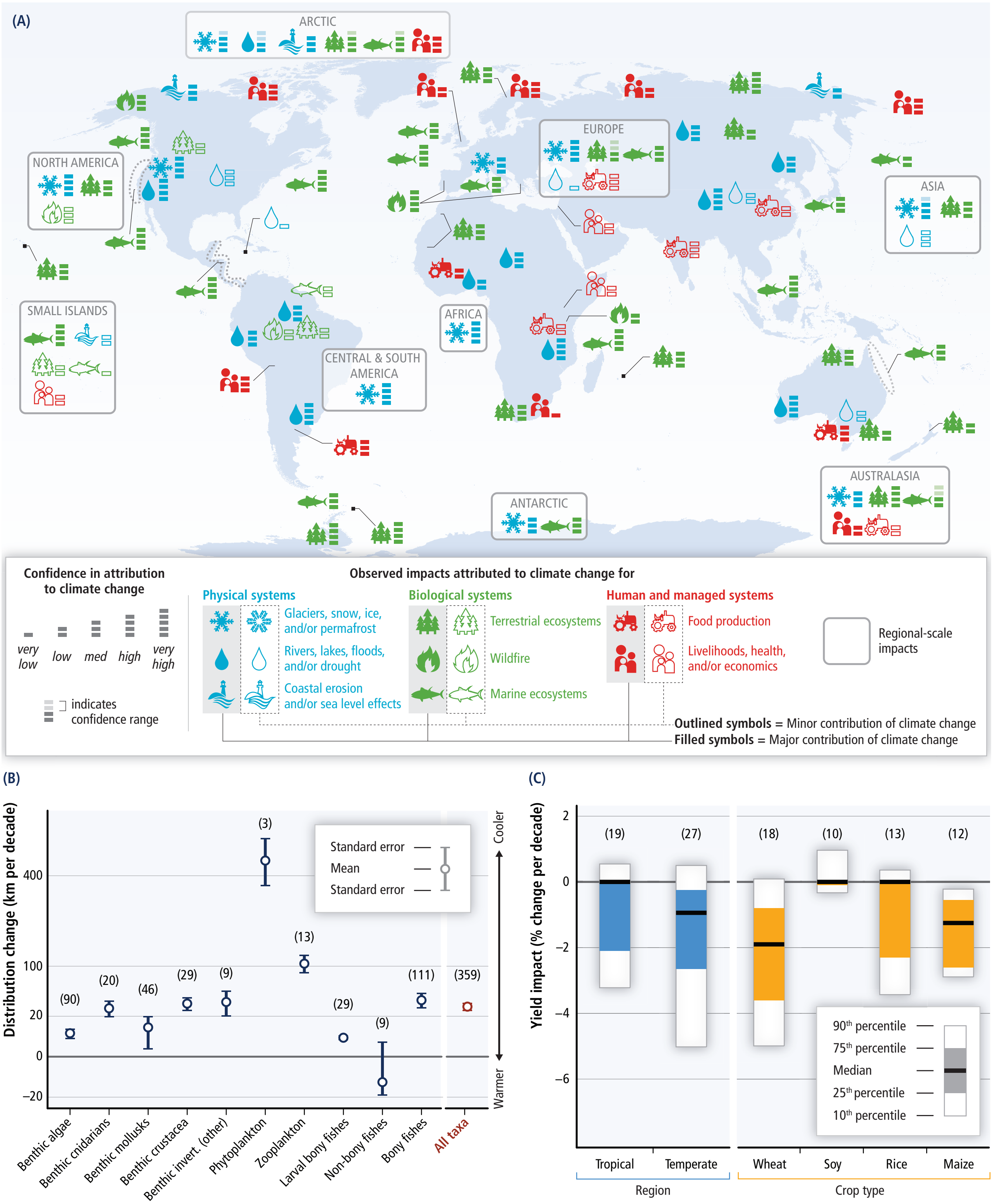

Figure SPM.2 | Widespread impacts in a changing world. (A) Global patterns of impacts in recent decades attributed to climate change, based on studies since the AR4. Impacts are shown at a range of geographic scales. Symbols indicate categories of attributed impacts, the relative contribution of climate change (major or minor) to the observed impact, and confidence in attribution. See supplementary Table SPM.A1 for descriptions of the impacts. (B) Average rates of change in distribution (km per decade) for marine taxonomic groups based on observations over 1900–2010. Positive distribution changes are consistent with warming (moving into previously cooler waters, generally poleward). The number of responses analyzed is given within parentheses for each category. (C) Summary of estimated impacts of observed climate changes on yields over 1960–2013 for four major crops in temperate and tropical regions, with the number of data points analyzed given within parentheses for each category. [Figures 7-2, 18-3, and MB-2] yields, or destruction of homes and indirectly through, for example, increased food prices and food insecurity. Observed positive effects for poor and marginalized people, which are limited and often indirect, include examples such as diversification of social networks and of agricultural practices.[15]

Violent conflict increases vulnerability to climate change (*medium evidence*, *high agreement*). Large-scale violent conflict harms assets that facilitate adaptation, including infrastructure, institutions, natural resources, social capital, and livelihood opportunities.[16]

A-2. Adaptation Experience

Throughout history, people and societies have adjusted to and coped with climate, climate variability, and extremes, with varying degrees of success. This section focuses on adaptive human responses to observed and projected climate-change impacts, which can also address broader risk-reduction and development objectives.

Adaptation is becoming embedded in some planning processes, with more limited implementation of responses (*high confidence*). Engineered and technological options are commonly implemented adaptive responses, often integrated within existing programs such as disaster risk management and water management. There is increasing recognition of the value of social, institutional, and ecosystem-based measures and of the extent of constraints to adaptation. Adaptation options adopted to date continue to emphasize incremental adjustments and co-benefits and are starting to emphasize flexibility and learning (*medium evidence*, *medium agreement*). Most assessments of adaptation have been restricted to impacts, vulnerability, and adaptation planning, with very few assessing the processes of implementation or the effects of adaptation actions (*medium evidence*, *high agreement*).[17]

Adaptation experience is accumulating across regions in the public and private sector and within communities (*high confidence*). Governments at various levels are starting to develop adaptation plans and policies and to integrate climate-change considerations into broader development plans. Examples of adaptation across regions include the following:

- In Africa, most national governments are initiating governance systems for adaptation. Disaster risk management, adjustments in technologies and infrastructure, ecosystem-based approaches, basic public health measures, and livelihood diversification are reducing vulnerability, although efforts to date tend to be isolated.[18]
- In Europe, adaptation policy has been developed across all levels of government, with some adaptation planning integrated into coastal and water management, into environmental protection and land planning, and into disaster risk management.[19]
- In Asia, adaptation is being facilitated in some areas through mainstreaming climate adaptation action into subnational development planning, early warning systems, integrated water resources management, agroforestry, and coastal reforestation of mangroves.[20]
- In Australasia, planning for sea level rise, and in southern Australia for reduced water availability, is becoming adopted widely. Planning for sea level rise has evolved considerably over the past 2 decades and shows a diversity of approaches, although its implementation remains piecemeal.[21]
- In North America, governments are engaging in incremental adaptation assessment and planning, particularly at the municipal level. Some proactive adaptation is occurring to protect longer-term investments in energy and public infrastructure.[22]
- In Central and South America, ecosystem-based adaptation including protected areas, conservation agreements, and community management of natural areas is occurring. Resilient crop varieties, climate forecasts, and integrated water resources management are being adopted within the agricultural sector in some areas.[23]

[15] 8.2-3, 9.3, 11.3, 13.1-3, 22.3, 24.4, 26.8
[16] 12.5, 19.2, 19.6
[17] 4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 14.1, 14.3-4, 15.2-5, 17.2-3, 21.3, 21.5, 22.4, 23.7, 25.4, 26.8-9, 30.6, Boxes 25-1, 25-2, 25-9, and CC-EA
[18] 22.4
[19] 23.7, Boxes 5-1 and 23-3
[20] 24.4-6, 24.9 Box CC-TC
[21] 25.4, 25.10, Table 25-2, Boxes 25-1, 25-2, and 25-9
[22] 26.7-9
[23] 27.3

- In the Arctic, some communities have begun to deploy adaptive co-management strategies and communications infrastructure, combining traditional and scientific knowledge.[24]
- In small islands, which have diverse physical and human attributes, community-based adaptation has been shown to generate larger benefits when delivered in conjunction with other development activities.[25]
- In the ocean, international cooperation and marine spatial planning are starting to facilitate adaptation to climate change, with constraints from challenges of spatial scale and governance issues.[26]

A-3. The Decision-making Context

Climate variability and extremes have long been important in many decision-making contexts. Climate-related risks are now evolving over time due to both climate change and development. This section builds from existing experience with decision making and risk management. It creates a foundation for understanding the report's assessment of future climate-related risks and potential responses.

Responding to climate-related risks involves decision making in a changing world, with continuing uncertainty about the severity and timing of climate-change impacts and with limits to the effectiveness of adaptation (*high confidence*). Iterative risk management is a useful framework for decision making in complex situations characterized by large potential consequences, persistent uncertainties, long timeframes, potential for learning, and multiple climatic and non-climatic influences changing over time. See Figure SPM.3. Assessment of the widest possible range of potential impacts, including low-probability outcomes with large consequences, is central to understanding the benefits and trade-offs of alternative risk management actions. The complexity of adaptation actions across scales and contexts means that monitoring and learning are important components of effective adaptation.[27]

Adaptation and mitigation choices in the near term will affect the risks of climate change throughout the 21st century (*high confidence*). Figure SPM.4 illustrates projected warming under a low-emission mitigation scenario and a high-emission scenario [Representative Concentration Pathways (RCPs) 2.6 and 8.5], along with observed temperature changes. The benefits of adaptation and mitigation occur over different but overlapping timeframes. Projected global temperature increase over the next few decades is similar across emission scenarios (Figure SPM.4B).[28] During this near-term period, risks will evolve as socioeconomic trends interact with the changing climate. Societal

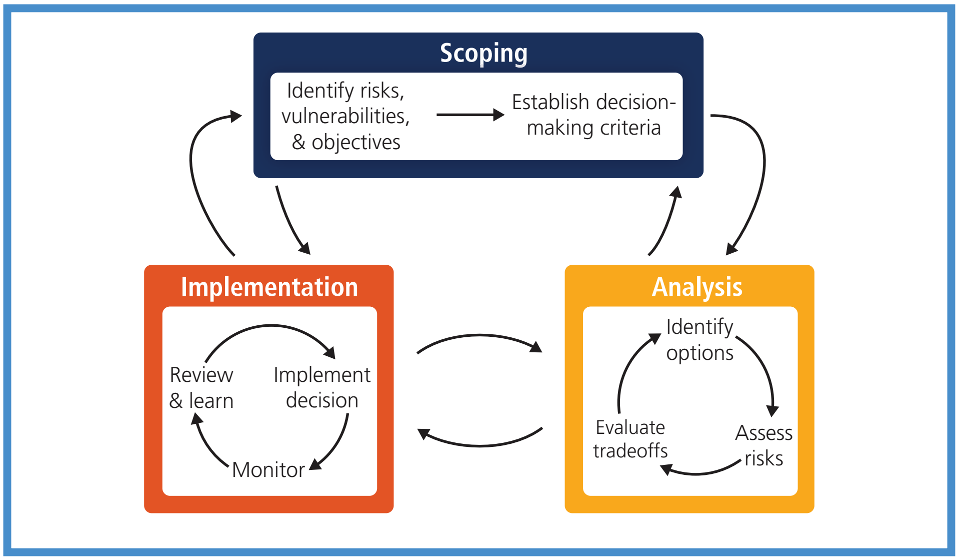

Figure SPM.3 | Climate-change adaptation as an iterative risk management process with multiple feedbacks. People and knowledge shape the process and its outcomes. [Figure 2-1]

[24] 28.2, 28.4
[25] 29.3, 29.6, Table 29-3, Figure 29-1
[26] 30.6
[27] 2.1-4, 3.6, 14.1-3, 15.2-4, 16.2-4, 17.1-3, 17.5, 20.6, 22.4, 25.4, Figure 1-5
[28] WGI AR5 11.3

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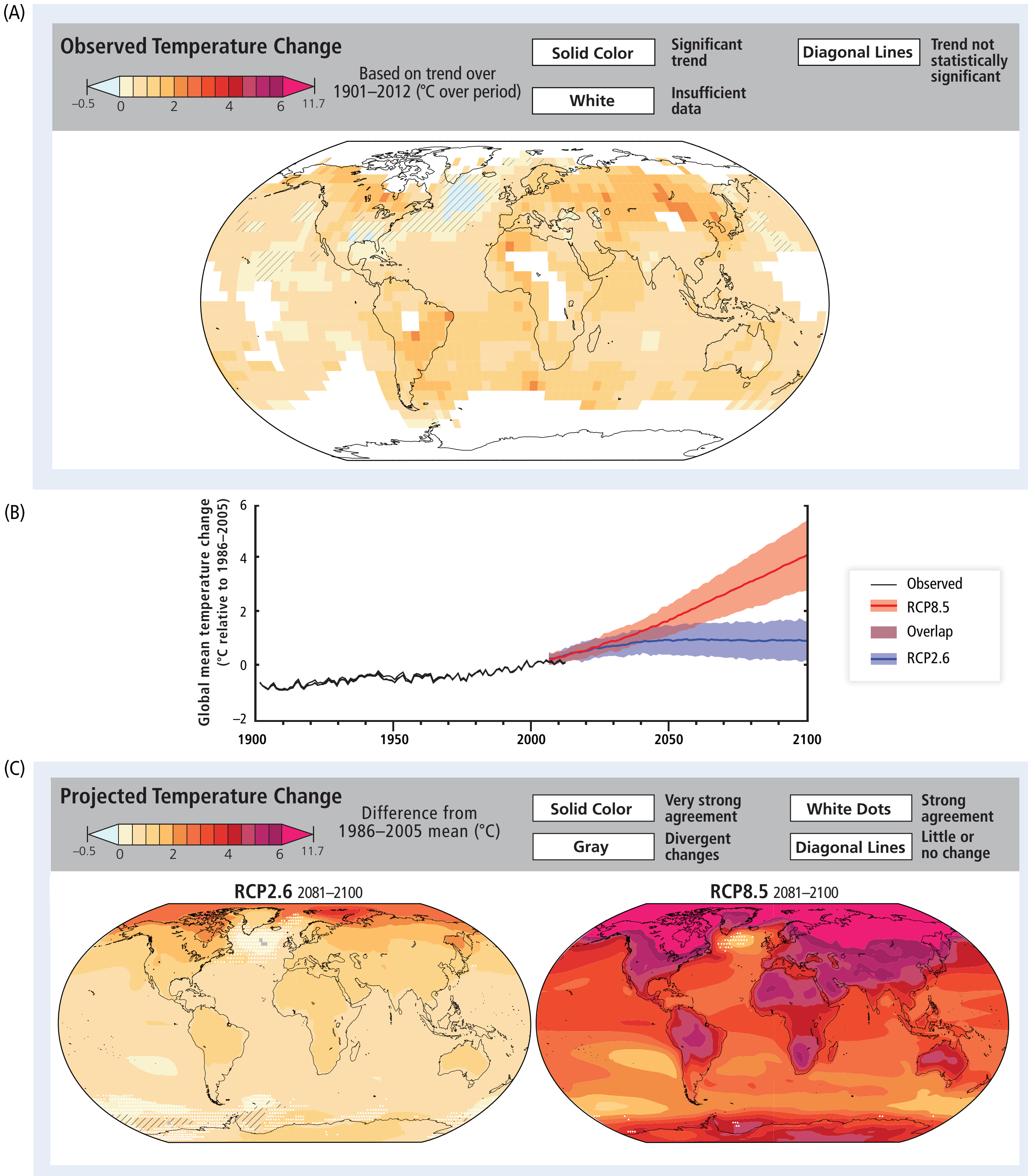

Figure SPM.4 | Observed and projected changes in annual average surface temperature. This figure informs understanding of climate-related risks in the WGII AR5. It illustrates temperature change observed to date and projected warming under continued high emissions and under ambitious mitigation.

Figure SPM.4 Technical Details

(A) Map of observed annual average temperature change from 1901–2012, derived from a linear trend where sufficient data permit a robust estimate; other areas are white. Solid colors indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. Observed data (range of grid-point values: –0.53 to 2.50°C over period) are from WGI AR5 Figures SPM.1 and 2.21. (B) Observed and projected future global annual average temperature relative to 1986–2005. Observed warming from 1850–1900 to 1986–2005 is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C). Black lines show temperature estimates from three datasets. Blue and red lines and shading denote the ensemble mean and ±1.64 standard deviation range, based on CMIP5 simulations from 32 models for RCP2.6 and 39 models for RCP8.5. (C) CMIP5 multi-model mean projections of annual average temperature changes for 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data (range of grid-point values across RCP2.6 and 8.5: 0.06 to 11.71°C) from WGI AR5 Figure SPM.8, with full description of methods in Box CC-RC. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC; WGI AR5 2.4, Figures SPM.1, SPM.7, and 2.21]

responses, particularly adaptations, will influence near-term outcomes. In the second half of the 21st century and beyond, global temperature increase diverges across emission scenarios (Figure SPM.4B and 4C).[29] For this longer-term period, near-term and longer-term adaptation and mitigation, as well as development pathways, will determine the risks of climate change.[30]

Assessment of risks in the WGII AR5 relies on diverse forms of evidence. Expert judgment is used to integrate evidence into evaluations of risks. Forms of evidence include, for example, empirical observations, experimental results, process-based understanding, statistical approaches, and simulation and descriptive models. Future risks related to climate change vary substantially across plausible alternative development pathways, and the relative importance of development and climate change varies by sector, region, and time period (*high confidence*). Scenarios are useful tools for characterizing possible future socioeconomic pathways, climate change and its risks, and policy implications. Climate-model projections informing evaluations of risks in this report are generally based on the RCPs (Figure SPM.4), as well as the older IPCC *Special Report on Emission Scenarios* (SRES) scenarios.[31]

Uncertainties about future vulnerability, exposure, and responses of interlinked human and natural systems are large (*high confidence*). This motivates exploration of a wide range of socioeconomic futures in assessments of risks. Understanding future vulnerability, exposure, and response capacity of interlinked human and natural systems is challenging due to the number of interacting social, economic, and cultural factors, which have been incompletely considered to date. These factors include wealth and its distribution across society, demographics, migration, access to technology and information, employment patterns, the quality of adaptive responses, societal values, governance structures, and institutions to resolve conflicts. International dimensions such as trade and relations among states are also important for understanding the risks of climate change at regional scales.[32]

B: FUTURE RISKS AND OPPORTUNITIES FOR ADAPTATION

This section presents future risks and more limited potential benefits across sectors and regions, over the next few decades and in the second half of the 21st century and beyond. It examines how they are affected by the magnitude and rate of climate change and by socioeconomic choices. It also assesses opportunities for reducing impacts and managing risks through adaptation and mitigation.

B-1. Key Risks across Sectors and Regions

Key risks are potentially severe impacts relevant to Article 2 of the United Nations Framework Convention on Climate Change, which refers to "dangerous anthropogenic interference with the climate system." Risks are considered key due to high hazard or high vulnerability of societies and systems exposed, or both. Identification of key risks was based on expert judgment using the following specific criteria: large magnitude,

[29] WGI AR5 12.4 and Table SPM.2
[30] 2.5, 21.2-3, 21.5, Box CC-RC
[31] 1.1, 1.3, 2.2-3, 19.6, 20.2, 21.3, 21.5, 26.2, Box CC-RC; WGI AR5 Box SPM.1
[32] 11.3, 12.6, 21.3-5, 25.3-4, 25.11, 26.2

Assessment Box SPM.1 | Human Interference with the Climate System

Human influence on the climate system is clear.[33] Yet determining whether such influence constitutes "dangerous anthropogenic interference" in the words of Article 2 of the UNFCCC involves both risk assessment and value judgments. This report assesses risks across contexts and through time, providing a basis for judgments about the level of climate change at which risks become dangerous.

Five integrative reasons for concern (RFCs) provide a framework for summarizing key risks across sectors and regions. First identified in the IPCC Third Assessment Report, the RFCs illustrate the implications of warming and of adaptation limits for people, economies, and ecosystems. They provide one starting point for evaluating dangerous anthropogenic interference with the climate system. Risks for each RFC, updated based on assessment of the literature and expert judgments, are presented below and in Assessment Box SPM.1 Figure 1. All temperatures below are given as global average temperature change relative to 1986–2005 ("recent").[34]

1) **Unique and threatened systems**: Some unique and threatened systems, including ecosystems and cultures, are already at risk from climate change (*high confidence*). The number of such systems at risk of severe consequences is higher with additional warming of around 1°C. Many species and systems with limited adaptive capacity are subject to very high risks with additional warming of 2°C, particularly Arctic-sea-ice and coral-reef systems.

2) **Extreme weather events**: Climate-change-related risks from extreme events, such as heat waves, extreme precipitation, and coastal flooding, are already moderate (*high confidence*) and high with 1°C additional warming (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures (*high confidence*).

3) **Distribution of impacts**: Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Risks are already moderate because of regionally differentiated climate-change impacts on crop production in particular (*medium* to *high confidence*). Based on projected decreases in regional crop yields and water availability, risks of unevenly distributed impacts are high for additional warming above 2°C (*medium confidence*).

4) **Global aggregate impacts**: Risks of global aggregate impacts are moderate for additional warming between 1–2°C, reflecting impacts to both Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss with associated loss of ecosystem goods and services results in high risks around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above.

5) **Large-scale singular events**: With increasing warming, some physical systems or ecosystems may be at risk of abrupt and irreversible changes. Risks associated with such tipping points become moderate between 0–1°C additional warming, due to early warning signs that both warm-water coral reef and Arctic ecosystems are already experiencing irreversible regime shifts (*medium confidence*). Risks increase disproportionately as temperature increases between 1–2°C additional warming and become high above 3°C, due to the potential for a large and irreversible sea level rise from ice sheet loss. For sustained warming greater than some threshold,[35] near-complete loss of the Greenland ice sheet would occur over a millennium or more, contributing up to 7 m of global mean sea level rise.

high probability, or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation. Key risks are integrated into five complementary and overarching reasons for concern (RFCs) in Assessment Box SPM.1.

The key risks that follow, all of which are identified with *high confidence*, span sectors and regions. Each of these key risks contributes to one or more RFCs.[36]

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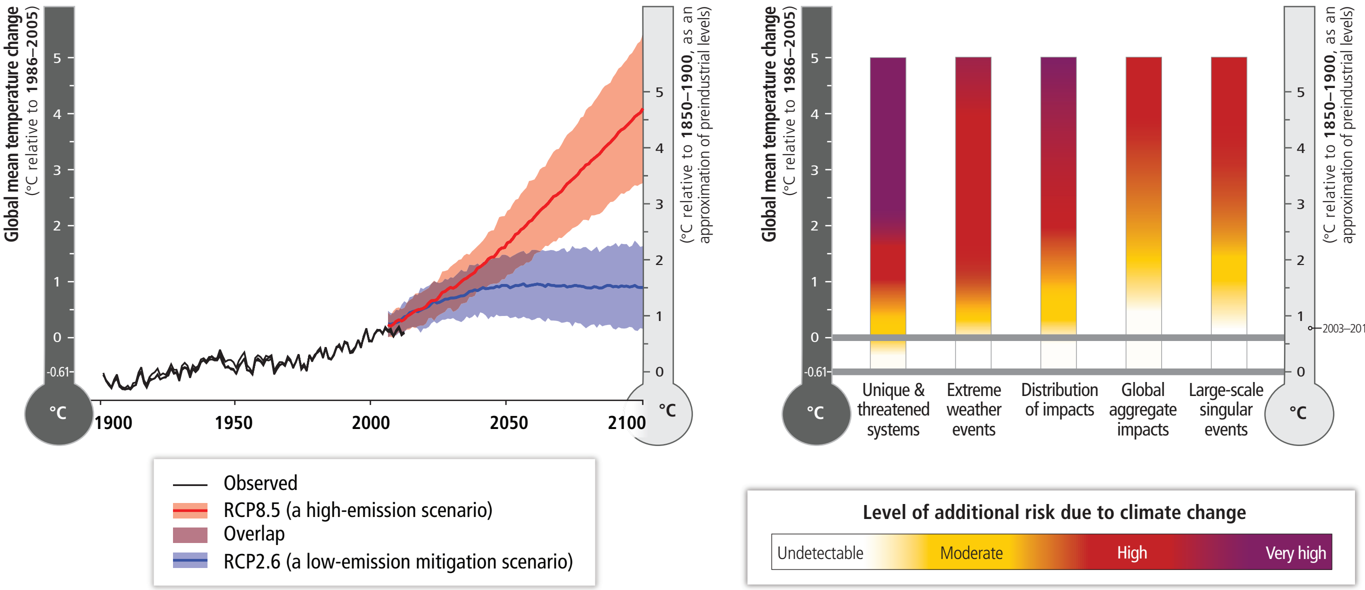
[33] WGI AR5 SPM, 2.2, 6.3, 10.3-6, 10.9

[34] 18.6, 19.6; observed warming from 1850–1900 to 1986–2005 is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C). [WGI AR5 2.4]

[35] Current estimates indicate that this threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) sustained global mean warming above preindustrial levels. [WGI AR5 SPM, 5.8, 13.4-5]

[36] 19.2-4, 19.6, Table 19-4, Boxes 19-2 and CC-KR



Assessment Box SPM.1 Figure 1 | A global perspective on climate-related risks. Risks associated with reasons for concern are shown at right for increasing levels of climate change. The color shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. Undetectable risk (white) indicates no associated impacts are detectable and attributable to climate change. Moderate risk (yellow) indicates that associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks. High risk (red) indicates severe and widespread impacts, also accounting for the other specific criteria for key risks. Purple, introduced in this assessment, shows that very high risk is indicated by all specific criteria for key risks. [Figure 19-4] For reference, past and projected global annual average surface temperature is shown at left, as in Figure SPM.4. [Figure RC-1, Box CC-RC; WGI AR5 Figures SPM.1 and SPM.7] Based on the longest global surface temperature dataset available, the observed change between the average of the period 1850–1900 and of the AR5 reference period (1986–2005) is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C) [WGI AR5 SPM, 2.4], which is used here as an approximation of the change in global mean surface temperature since preindustrial times, referred to as the period before 1750. [WGI and WGII AR5 glossaries]

i) Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise.[37] [RFC 1-5]

ii) Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions.[38] [RFC 2 and 3]

iii) Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services.[39] [RFC 2-4]

iv) Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas.[40] [RFC 2 and 3]

v) Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings.[41] [RFC 2-4]

vi) Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions.[42] [RFC 2 and 3]

vii) Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic.[43] [RFC 1, 2, and 4]

viii) Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods.[44] [RFC 1, 3, and 4]

Many key risks constitute particular challenges for the least developed countries and vulnerable communities, given their limited ability to cope.

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[37] 5.4, 8.2, 13.2, 19.2-4, 19.6-7, 24.4-5, 26.7-8, 29.3, 30.3, Tables 19-4 and 26-1, Figure 26-2, Boxes 25-1, 25-7, and CC-KR
[38] 3.4-5, 8.2, 13.2, 19.6, 25.10, 26.3, 26.8, 27.3, Tables 19-4 and 26-1, Boxes 25-8 and CC-KR
[39] 5.4, 8.1-2, 9.3, 10.2-3, 12.6, 19.6, 23.9, 25.10, 26.7-8, 28.3, Table 19-4, Boxes CC-KR and CC-HS
[40] 8.1-2, 11.3-4, 11.6, 13.2, 19.3, 19.6, 23.5, 24.4, 25.8, 26.6, 26.8, Tables 19-4 and 26-1, Boxes CC-KR and CC-HS
[41] 3.5, 7.4-5, 8.2-3, 9.3, 11.3, 11.6, 13.2, 19.3-4, 19.6, 22.3, 24.4, 25.5, 25.7, 26.5, 26.8, 27.3, 28.2, 28.4, Table 19-4, Box CC-KR
[42] 3.4-5, 9.3, 12.2, 13.2, 19.3, 19.6, 24.4, 25.7, 26.8, Table 19-4, Boxes 25-5 and CC-KR
[43] 5.4, 6.3, 7.4, 9.3, 19.5-6, 22.3, 25.6, 27.3, 28.2-3, 29.3, 30.5-7, Table 19-4, Boxes CC-OA, CC-CR, CC-KR, and CC-HS
[44] 4.3, 9.3, 19.3-6, 22.3, 25.6, 27.3, 28.2-3, Table 19-4, Boxes CC-KR and CC-WE

Increasing magnitudes of warming increase the likelihood of severe, pervasive, and irreversible impacts. Some risks of climate change are considerable at 1 or 2°C above preindustrial levels (as shown in Assessment Box SPM.1). Global climate change risks are high to very high with global mean temperature increase of 4°C or more above preindustrial levels in all reasons for concern (Assessment Box SPM.1), and include severe and widespread impacts on unique and threatened systems, substantial species extinction, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year (*high confidence*). The precise levels of climate change sufficient to trigger tipping points (thresholds for abrupt and irreversible change) remain uncertain, but the risk associated with crossing multiple tipping points in the earth system or in interlinked human and natural systems increases with rising temperature (*medium confidence*).[45]

The overall risks of climate change impacts can be reduced by limiting the rate and magnitude of climate change. Risks are reduced substantially under the assessed scenario with the lowest temperature projections (RCP2.6 – low emissions) compared to the highest temperature projections (RCP8.5 – high emissions), particularly in the second half of the 21st century (*very high confidence*). Reducing climate change can also reduce the scale of adaptation that might be required. Under all assessed scenarios for adaptation and mitigation, some risk from adverse impacts remains (*very high confidence*).[46]

B-2. Sectoral Risks and Potential for Adaptation

Climate change is projected to amplify existing climate-related risks and create new risks for natural and human systems. Some of these risks will be limited to a particular sector or region, and others will have cascading effects. To a lesser extent, climate change is also projected to have some potential benefits.

Freshwater resources

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas concentrations (*robust evidence*, *high agreement*). The fraction of global population experiencing water scarcity and the fraction affected by major river floods increase with the level of warming in the 21st century.[47]

Climate change over the 21st century is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*robust evidence*, *high agreement*), intensifying competition for water among sectors (*limited evidence*, *medium agreement*). In presently dry regions, drought frequency will *likely* increase by the end of the 21st century under RCP8.5 (*medium confidence*). In contrast, water resources are projected to increase at high latitudes (*robust evidence*, *high agreement*). Climate change is projected to reduce raw water quality and pose risks to drinking water quality even with conventional treatment, due to interacting factors: increased temperature; increased sediment, nutrient, and pollutant loadings from heavy rainfall; increased concentration of pollutants during droughts; and disruption of treatment facilities during floods (*medium evidence*, *high agreement*). Adaptive water management techniques, including scenario planning, learning-based approaches, and flexible and low-regret solutions, can help create resilience to uncertain hydrological changes and impacts due to climate change (*limited evidence*, *high agreement*).[48]

Terrestrial and freshwater ecosystems

A large fraction of both terrestrial and freshwater species faces increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other stressors, such as habitat modification, over-

[45] 4.2-3, 11.8, 19.5, 19.7, 26.5, Box CC-HS
[46] 3.4-5, 16.6, 17.2, 19.7, 20.3, 25.10, Tables 3-2, 8-3, and 8-6, Boxes 16-3 and 25-1
[47] 3.4-5, 26.3, Table 3-2, Box 25-8

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exploitation, pollution, and invasive species (*high confidence*). Extinction risk is increased under all RCP scenarios, with risk increasing with both magnitude and rate of climate change. Many species will be unable to track suitable climates under mid- and high-range rates of climate change (i.e., RCP4.5, 6.0, and 8.5) during the 21st century (*medium confidence*). Lower rates of change (i.e., RCP2.6) will pose fewer problems. See Figure SPM.5. Some species will adapt to new climates. Those that cannot adapt sufficiently fast will decrease in abundance or go extinct in part or all of their ranges. Management actions, such as maintenance of genetic diversity, assisted species migration and dispersal, manipulation of disturbance regimes (e.g., fires, floods), and reduction of other stressors, can reduce, but not eliminate, risks of impacts to terrestrial and freshwater ecosystems due to climate change, as well as increase the inherent capacity of ecosystems and their species to adapt to a changing climate (*high confidence*).[49]

Within this century, magnitudes and rates of climate change associated with medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5) pose high risk of abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, including wetlands (*medium confidence*). Examples that could lead to substantial impact on climate are the boreal-tundra Arctic system (*medium confidence*) and the Amazon forest (*low confidence*). Carbon stored in the terrestrial biosphere (e.g., in peatlands, permafrost, and forests) is susceptible to loss to the atmosphere as a result of climate change, deforestation, and ecosystem degradation (*high confidence*). Increased tree mortality and associated forest dieback is projected to occur in many regions over the 21st century, due to increased temperatures and drought (*medium confidence*). Forest dieback poses risks for carbon storage, biodiversity, wood production, water quality, amenity, and economic activity.[50]

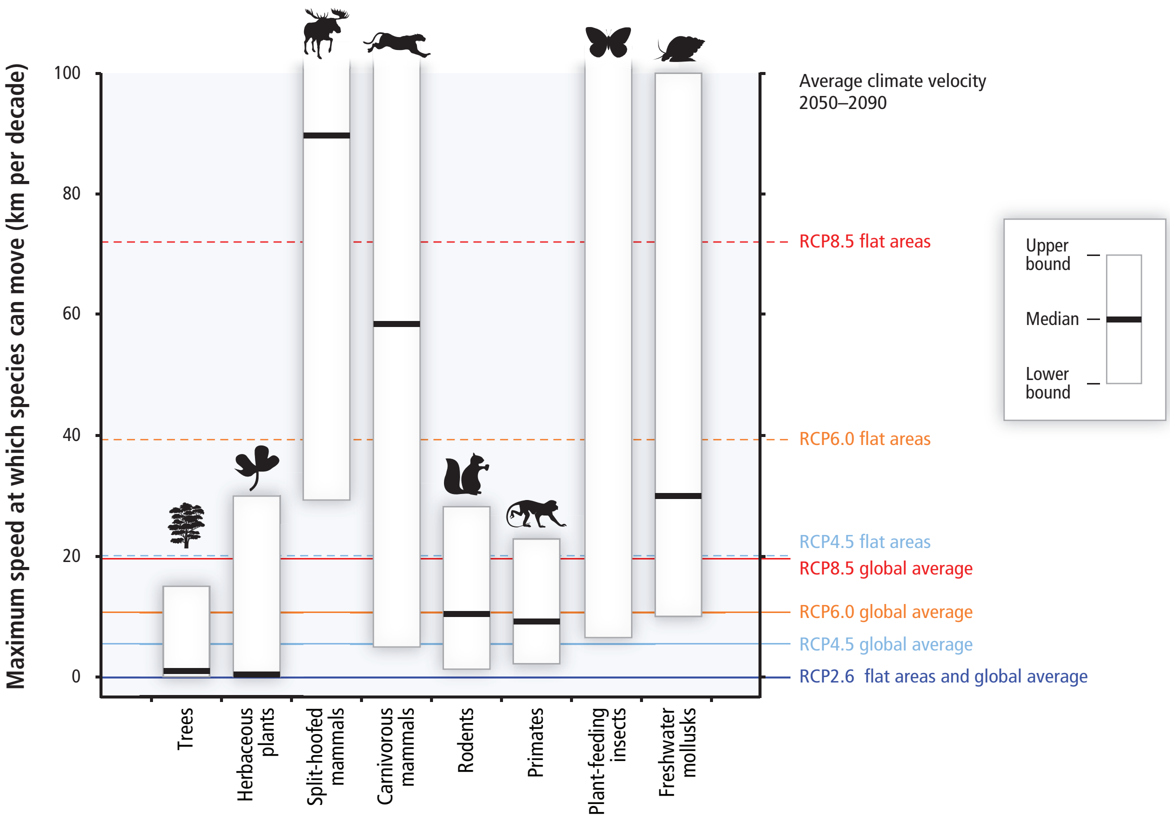

Figure SPM.5 | Maximum speeds at which species can move across landscapes (based on observations and models; vertical axis on left), compared with speeds at which temperatures are projected to move across landscapes (climate velocities for temperature; vertical axis on right). Human interventions, such as transport or habitat fragmentation, can greatly increase or decrease speeds of movement. White boxes with black bars indicate ranges and medians of maximum movement speeds for trees, plants, mammals, plant-feeding insects (median not estimated), and freshwater mollusks. For RCP2.6, 4.5, 6.0, and 8.5 for 2050–2090, horizontal lines show climate velocity for the global-land-area average and for large flat regions. Species with maximum speeds below each line are expected to be unable to track warming in the absence of human intervention. [Figure 4-5]

48 3.2, 3.4-6, 22.3, 23.9, 25.5, 26.3, Table 3-2, Table 23-3, Boxes 25-2, CC-RF, and CC-WE; WGI AR5 12.4

49 4.3-4, 25.6, 26.4, Box CC-RF

50 4.2-3, Figure 4-8, Boxes 4-2, 4-3, and 4-4

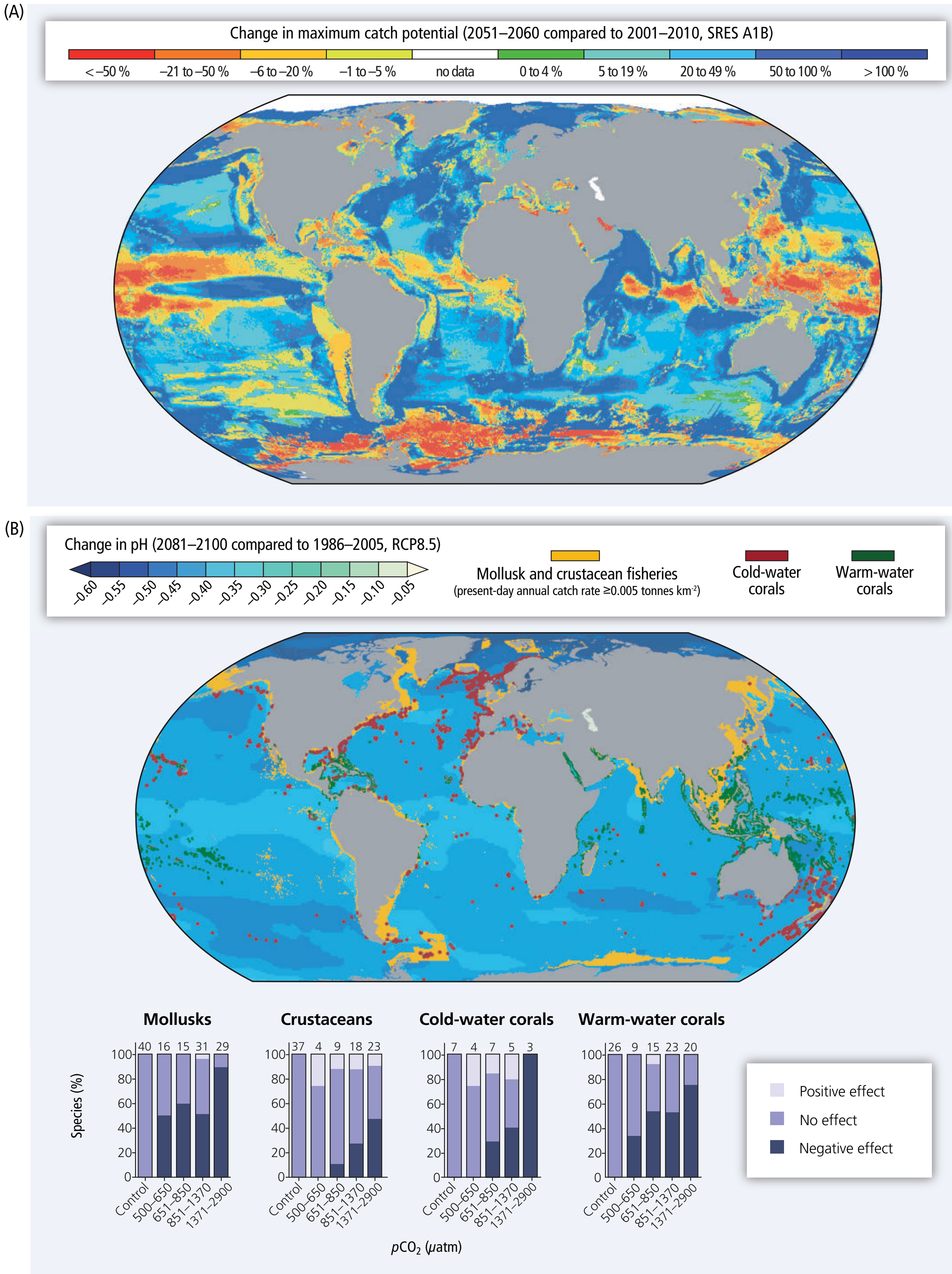
(A)
Change in maximum catch potential (2051–2060 compared to 2001–2010, SRES A1B)
< –50 %
–21 to –50 %
–6 to –20 %
–1 to –5 %
no data
0 to 4 %
5 to 19 %
20 to 49 %
50 to 100 %
> 100 %
(B)
Change in pH (2081–2100 compared to 1986–2005, RCP8.5)
–0.60 –0.55 –0.50 –0.45 –0.40 –0.35 –0.30 –0.25 –0.20 –0.15 –0.10 –0.05
Mollusk and crustacean fisheries
(present-day annual catch rate ≥0.005 tonnes km⁻²)
Cold-water corals
Warm-water corals
Mollusks
40 16 15 31 29
Crustaceans
37 4 9 18 23
Cold-water corals
7 4 7 5 3
Warm-water corals
26 9 15 23 20
Species (%)
0 20 40 60 80 100
Control
500–650
651–850
851–1370
1371–2900
pCO2 (μatm)
Positive effect
No effect
Negative effect

Figure SPM.6 | Climate change risks for fisheries. (A) Projected global redistribution of maximum catch potential of ~1000 exploited fish and invertebrate species. Projections compare the 10-year averages 2001–2010 and 2051–2060 using SRES A1B, without analysis of potential impacts of overfishing or ocean acidification. (B) Marine mollusk and crustacean fisheries (present-day estimated annual catch rates ≥0.005 tonnes km^{-2}) and known locations of cold- and warm-water corals, depicted on a global map showing the projected distribution of ocean acidification under RCP8.5 (pH change from 1986–2005 to 2081–2100). [WGI AR5 Figure SPM.8] The bottom panel compares sensitivity to ocean acidification across mollusks, crustaceans, and corals, vulnerable animal phyla with socioeconomic relevance (e.g., for coastal protection and fisheries). The number of species analyzed across studies is given for each category of elevated CO_2. For 2100, RCP scenarios falling within each CO_2 partial pressure (pCO_2) category are as follows: RCP4.5 for 500–650 μatm (approximately equivalent to ppm in the atmosphere), RCP6.0 for 651–850 μatm, and RCP8.5 for 851–1370 μatm. By 2150, RCP8.5 falls within the 1371–2900 μatm category. The control category corresponds to 380 μatm. [6.1, 6.3, 30.5, Figures 6-10 and 6-14; WGI AR5 Box SPM.1]

Coastal systems and low-lying areas

Due to sea level rise projected throughout the 21st century and beyond, coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion (*very high confidence*). The population and assets projected to be exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, and urbanization (*high confidence*). The relative costs of coastal adaptation vary strongly among and within regions and countries for the 21st century. Some low-lying developing countries and small island states are expected to face very high impacts that, in some cases, could have associated damage and adaptation costs of several percentage points of GDP.[51]

Marine systems

Due to projected climate change by the mid 21st century and beyond, global marine-species redistribution and marine-biodiversity reduction in sensitive regions will challenge the sustained provision of fisheries productivity and other ecosystem services (*high confidence*). Spatial shifts of marine species due to projected warming will cause high-latitude invasions and high local-extinction rates in the tropics and semi-enclosed seas (*medium confidence*). Species richness and fisheries catch potential are projected to increase, on average, at mid and high latitudes (*high confidence*) and decrease at tropical latitudes (*medium confidence*). See Figure SPM.6A. The progressive expansion of oxygen minimum zones and anoxic "dead zones" is projected to further constrain fish habitat. Open-ocean net primary production is projected to redistribute and, by 2100, fall globally under all RCP scenarios. Climate change adds to the threats of over-fishing and other non-climatic stressors, thus complicating marine management regimes (*high confidence*).[52]

For medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5), ocean acidification poses substantial risks to marine ecosystems, especially polar ecosystems and coral reefs, associated with impacts on the physiology, behavior, and population dynamics of individual species from phytoplankton to animals (*medium* to *high confidence*). Highly calcified mollusks, echinoderms, and reef-building corals are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*), with potentially detrimental consequences for fisheries and livelihoods. See Figure SPM.6B. Ocean acidification acts together with other global changes (e.g., warming, decreasing oxygen levels) and with local changes (e.g., pollution, eutrophication) (*high confidence*). Simultaneous drivers, such as warming and ocean acidification, can lead to interactive, complex, and amplified impacts for species and ecosystems.[53]

Food security and food production systems

For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation is projected to negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (*medium confidence*). Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10%, and about 10% of projections showing yield losses of more than

[51] 5.3-5, 8.2, 22.3, 24.4, 25.6, 26.3, 26.8, Table 26-1, Box 25-1

[52] 6.3-5, 7.4, 25.6, 28.3, 30.6-7, Boxes CC-MB and CC-PP

[53] 5.4, 6.3-5, 22.3, 25.6, 28.3, 30.5, Boxes CC-CR, CC-OA, and TS.7

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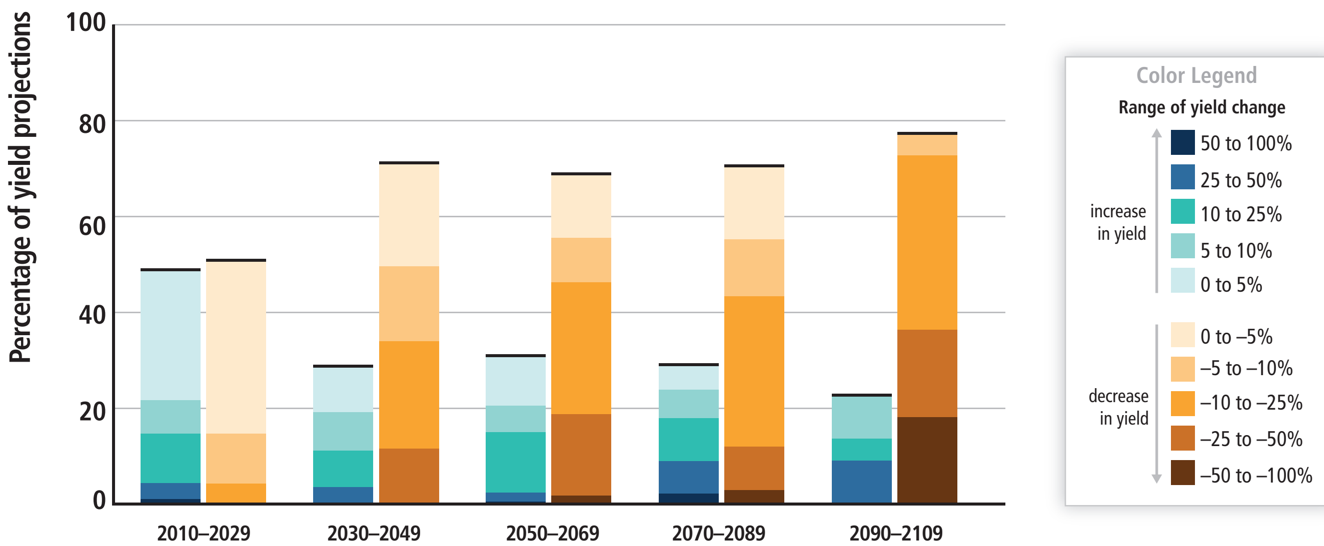


Figure SPM.7 | Summary of projected changes in crop yields, due to climate change over the 21st century. The figure includes projections for different emission scenarios, for tropical and temperate regions, and for adaptation and no-adaptation cases combined. Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. For five timeframes in the near term and long term, data (n=1090) are plotted in the 20-year period on the horizontal axis that includes the midpoint of each future projection period. Changes in crop yields are relative to late-20th-century levels. Data for each timeframe sum to 100%. [Figure 7-5]

25%, compared to the late 20th century. After 2050 the risk of more severe yield impacts increases and depends on the level of warming. See Figure SPM.7. Climate change is projected to progressively increase inter-annual variability of crop yields in many regions. These projected impacts will occur in the context of rapidly rising crop demand.[54]

All aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (*high confidence*). Redistribution of marine fisheries catch potential towards higher latitudes poses risk of reduced supplies, income, and employment in tropical countries, with potential implications for food security (*medium confidence*). Global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (*high confidence*). Risks to food security are generally greater in low-latitude areas.[55]

Urban areas

Many global risks of climate change are concentrated in urban areas (*medium confidence*). Steps that build resilience and enable sustainable development can accelerate successful climate-change adaptation globally. Heat stress, extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, and water scarcity pose risks in urban areas for people, assets, economies, and ecosystems (*very high confidence*). Risks are amplified for those lacking essential infrastructure and services or living in poor-quality housing and exposed areas. Reducing basic service deficits, improving housing, and building resilient infrastructure systems could significantly reduce vulnerability and exposure in urban areas. Urban adaptation benefits from effective multi-level urban risk governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector, and appropriate financing and institutional development (*medium confidence*). Increased capacity, voice, and influence of low-income groups and vulnerable communities and their partnerships with local governments also benefit adaptation.[56]

[54] 7.4-5, 22.3, 24.4, 25.7, 26.5, Table 7-2, Figures 7-4, 7-5, 7-6, 7-7, and 7-8
[55] 6.3-5, 7.4-5, 9.3, 22.3, 24.4, 25.7, 26.5, Table 7-3, Figures 7-1, 7-4, and 7-7, Box 7-1
[56] 3.5, 8.2-4, 22.3, 24.4-5, 26.8, Table 8-2, Boxes 25-9 and CC-HS

Rural areas

Major future rural impacts are expected in the near term and beyond through impacts on water availability and supply, food security, and agricultural incomes, including shifts in production areas of food and non-food crops across the world (*high confidence*). These impacts are expected to disproportionately affect the welfare of the poor in rural areas, such as female-headed households and those with limited access to land, modern agricultural inputs, infrastructure, and education. Further adaptations for agriculture, water, forestry, and biodiversity can occur through policies taking account of rural decision-making contexts. Trade reform and investment can improve market access for small-scale farms (*medium confidence*).[57]

Key economic sectors and services

For most economic sectors, the impacts of drivers such as changes in population, age structure, income, technology, relative prices, lifestyle, regulation, and governance are projected to be large relative to the impacts of climate change (*medium evidence*, *high agreement*). Climate change is projected to reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*robust evidence*, *high agreement*). Climate change is projected to affect energy sources and technologies differently, depending on resources (e.g., water flow, wind, insolation), technological processes (e.g., cooling), or locations (e.g., coastal regions, floodplains) involved. More severe and/or frequent extreme weather events and/or hazard types are projected to increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in developing countries. Large-scale public-private risk reduction initiatives and economic diversification are examples of adaptation actions.[58]

Global economic impacts from climate change are difficult to estimate. Economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors.[59] With these recognized limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income (±1 standard deviation around the mean) (*medium evidence*, *medium agreement*). Losses are *more likely than not* to be greater, rather than smaller, than this range (*limited evidence*, *high agreement*). Additionally, there are large differences between and within countries. Losses accelerate with greater warming (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. Estimates of the incremental economic impact of emitting carbon dioxide lie between a few dollars and several hundreds of dollars per tonne of carbon[60] (*robust evidence*, *medium agreement*). Estimates vary strongly with the assumed damage function and discount rate.[61]

Human health

Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*). Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change (*high confidence*). Examples include greater likelihood of injury, disease, and death due to more intense heat waves and fires (*very high confidence*); increased likelihood of under-nutrition resulting from diminished food production in poor regions (*high confidence*); risks from lost work capacity and reduced labor productivity in vulnerable populations; and increased risks from food- and water-borne diseases (*very high confidence*) and

[57] 9.3, 25.9, 26.8, 28.2, 28.4, Box 25-5

[58] 3.5, 10.2, 10.7, 10.10, 17.4-5, 25.7, 26.7-9, Box 25-7

[59] Disaster loss estimates are lower-bound estimates because many impacts, such as loss of human lives, cultural heritage, and ecosystem services, are difficult to value and monetize, and thus they are poorly reflected in estimates of losses. Impacts on the informal or undocumented economy as well as indirect economic effects can be very important in some areas and sectors, but are generally not counted in reported estimates of losses. [SREX 4.5]

[60] 1 tonne of carbon = 3.667 tonne of CO_2

[61] 10.9

vector-borne diseases (*medium confidence*). Positive effects are expected to include modest reductions in cold-related mortality and morbidity in some areas due to fewer cold extremes (*low confidence*), geographical shifts in food production (*medium confidence*), and reduced capacity of vectors to transmit some diseases. But globally over the 21st century, the magnitude and severity of negative impacts are projected to increasingly outweigh positive impacts (*high confidence*). The most effective vulnerability reduction measures for health in the near term are programs that implement and improve basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*). By 2100 for the high-emission scenario RCP8.5, the combination of high temperature and humidity in some areas for parts of the year is projected to compromise normal human activities, including growing food or working outdoors (*high confidence*).[62]

Human security

Climate change over the 21st century is projected to increase displacement of people (*medium evidence*, *high agreement*). Displacement risk increases when populations that lack the resources for planned migration experience higher exposure to extreme weather events, in both rural and urban areas, particularly in developing countries with low income. Expanding opportunities for mobility can reduce vulnerability for such populations. Changes in migration patterns can be responses to both extreme weather events and longer-term climate variability and change, and migration can also be an effective adaptation strategy. There is *low confidence* in quantitative projections of changes in mobility, due to its complex, multi-causal nature.[63]

Climate change can indirectly increase risks of violent conflicts in the form of civil war and inter-group violence by amplifying well-documented drivers of these conflicts such as poverty and economic shocks (*medium confidence*). Multiple lines of evidence relate climate variability to these forms of conflict.[64]

The impacts of climate change on the critical infrastructure and territorial integrity of many states are expected to influence national security policies (*medium evidence*, *medium agreement*). For example, land inundation due to sea level rise poses risks to the territorial integrity of small island states and states with extensive coastlines. Some transboundary impacts of climate change, such as changes in sea ice, shared water resources, and pelagic fish stocks, have the potential to increase rivalry among states, but robust national and intergovernmental institutions can enhance cooperation and manage many of these rivalries.[65]

Livelihoods and poverty

Throughout the 21st century, climate-change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security, and prolong existing and create new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*). Climate-change impacts are expected to exacerbate poverty in most developing countries and create new poverty pockets in countries with increasing inequality, in both developed and developing countries. In urban and rural areas, wage-labor-dependent poor households that are net buyers of food are expected to be particularly affected due to food price increases, including in regions with high food insecurity and high inequality (particularly in Africa), although the agricultural self-employed could benefit. Insurance programs, social protection measures, and disaster risk management may enhance long-term livelihood resilience among poor and marginalized people, if policies address poverty and multidimensional inequalities.[66]

B-3. Regional Key Risks and Potential for Adaptation

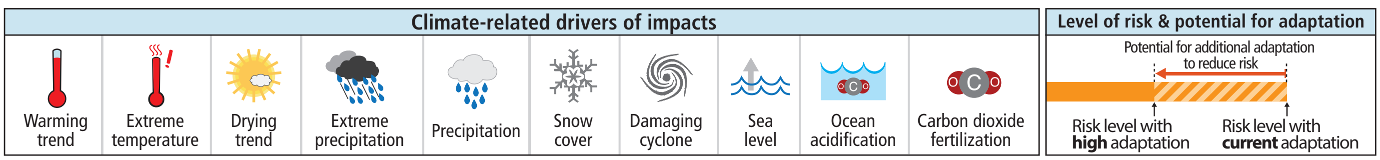
Risks will vary through time across regions and populations, dependent on myriad factors including the extent of adaptation and mitigation. A selection of key regional risks identified with *medium* to *high confidence* is presented in Assessment Box SPM.2. For extended summary of regional risks and potential benefits, see Technical Summary Section B-3 and WGII AR5 Part B: Regional Aspects.

Assessment Box SPM.2 | Regional Key Risks

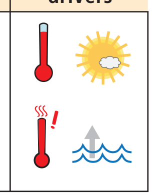
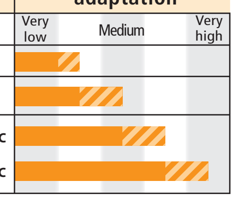
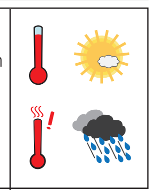
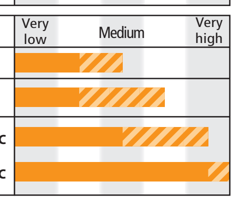
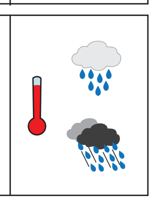
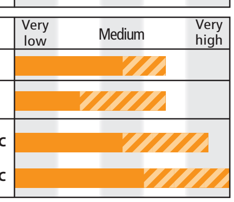
The accompanying Assessment Box SPM.2 Table 1 highlights several representative key risks for each region. Key risks have been identified based on assessment of the relevant scientific, technical, and socioeconomic literature detailed in supporting chapter sections. Identification of key risks was based on expert judgment using the following specific criteria: large magnitude, high probability, or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation.

For each key risk, risk levels were assessed for three timeframes. For the present, risk levels were estimated for current adaptation and a hypothetical highly adapted state, identifying where current adaptation deficits exist. For two future timeframes, risk levels were estimated for a continuation of current adaptation and for a highly adapted state, representing the potential for and limits to adaptation. The risk levels integrate probability and consequence over the widest possible range of potential outcomes, based on available literature. These potential outcomes result from the interaction of climate-related hazards, vulnerability, and exposure. Each risk level reflects total risk from climatic and non-climatic factors. Key risks and risk levels vary across regions and over time, given differing socioeconomic development pathways, vulnerability and exposure to hazards, adaptive capacity, and risk perceptions. Risk levels are not necessarily comparable, especially across regions, because the assessment considers potential impacts and adaptation in different physical, biological, and human systems across diverse contexts. This assessment of risks acknowledges the importance of differences in values and objectives in interpretation of the assessed risk levels.

Assessment Box SPM.2 Table 1 | Key regional risks from climate change and the potential for reducing risks through adaptation and mitigation. Each key risk is characterized as very low to very high for three timeframes: the present, near term (here, assessed over 2030–2040), and longer term (here, assessed over 2080–2100). In the near term, projected levels of global mean temperature increase do not diverge substantially for different emission scenarios. For the longer term, risk levels are presented for two scenarios of global mean temperature increase (2°C and 4°C above preindustrial levels). These scenarios illustrate the potential for mitigation and adaptation to reduce the risks related to climate change. Climate-related drivers of impacts are indicated by icons.



Africa

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Compounded stress on water resources facing significant strain from overexploitation and degradation at present and increased demand in the future, with drought stress exacerbated in drought-prone regions of Africa (*high confidence*) [22.3-4]	• Reducing non-climate stressors on water resources • Strengthening institutional capacities for demand management, groundwater assessment, integrated water-wastewater planning, and integrated land and water governance • Sustainable urban development		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high 
Reduced crop productivity associated with heat and drought stress, with strong adverse effects on regional, national, and household livelihood and food security, also given increased pest and disease damage and flood impacts on food system infrastructure (*high confidence*) [22.3-4]	• Technological adaptation responses (e.g., stress-tolerant crop varieties, irrigation, enhanced observation systems) • Enhancing smallholder access to credit and other critical production resources; Diversifying livelihoods • Strengthening institutions at local, national, and regional levels to support agriculture (including early warning systems) and gender-oriented policy • Agronomic adaptation responses (e.g., agroforestry, conservation agriculture)		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high 
Changes in the incidence and geographic range of vector- and water-borne diseases due to changes in the mean and variability of temperature and precipitation, particularly along the edges of their distribution (*medium confidence*) [22.3]	• Achieving development goals, particularly improved access to safe water and improved sanitation, and enhancement of public health functions such as surveillance • Vulnerability mapping and early warning systems • Coordination across sectors • Sustainable urban development		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high 

[62] 8.2, 11.3-8, 19.3, 22.3, 25.8, 26.6, Figure 25-5, Box CC-HS
[63] 9.3, 12.4, 19.4, 22.3, 25.9
[64] 12.5, 13.2, 19.4
[65] 12.5-6, 23.9, 25.9
[66] 8.1, 8.3-4, 9.3, 10.9, 13.2-4, 22.3, 26.8

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Assessment Box SPM.2 Table 1 (continued)

Continued next page →

Europe

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Increased economic losses and people affected by flooding in river basins and coasts, driven by increasing urbanization, increasing sea levels, coastal erosion, and peak river discharges (*high confidence*) [23.2-3, 23.7]	Adaptation can prevent most of the projected damages (*high confidence*). • Significant experience in hard flood-protection technologies and increasing experience with restoring wetlands • High costs for increasing flood protection • Potential barriers to implementation: demand for land in Europe and environmental and landscape concerns		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Increased water restrictions. Significant reduction in water availability from river abstraction and from groundwater resources, combined with increased water demand (e.g., for irrigation, energy and industry, domestic use) and with reduced water drainage and runoff as a result of increased evaporative demand, particularly in southern Europe (*high confidence*) [23.4, 23.7]	• Proven adaptation potential from adoption of more water-efficient technologies and of water-saving strategies (e.g., for irrigation, crop species, land cover, industries, domestic use) • Implementation of best practices and governance instruments in river basin management plans and integrated water management		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Increased economic losses and people affected by extreme heat events: impacts on health and well-being, labor productivity, crop production, air quality, and increasing risk of wildfires in southern Europe and in Russian boreal region (*medium confidence*) [23.3-7, Table 23-1]	• Implementation of warning systems • Adaptation of dwellings and workplaces and of transport and energy infrastructure • Reductions in emissions to improve air quality • Improved wildfire management • Development of insurance products against weather-related yield variations		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high

Asia

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Increased riverine, coastal, and urban flooding leading to widespread damage to infrastructure, livelihoods, and settlements in Asia (*medium confidence*) [24.4]	• Exposure reduction via structural and non-structural measures, effective land-use planning, and selective relocation • Reduction in the vulnerability of lifeline infrastructure and services (e.g., water, energy, waste management, food, biomass, mobility, local ecosystems, telecommunications) • Construction of monitoring and early warning systems; Measures to identify exposed areas, assist vulnerable areas and households, and diversify livelihoods • Economic diversification		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Increased risk of heat-related mortality (*high confidence*) [24.4]	• Heat health warning systems • Urban planning to reduce heat islands; Improvement of the built environment; Development of sustainable cities • New work practices to avoid heat stress among outdoor workers		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high
Increased risk of drought-related water and food shortage causing malnutrition (*high confidence*) [24.4]	• Disaster preparedness including early-warning systems and local coping strategies • Adaptive/integrated water resource management • Water infrastructure and reservoir development • Diversification of water sources including water re-use • More efficient use of water (e.g., improved agricultural practices, irrigation management, and resilient agriculture)		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low / Medium / Very high

SPM

Assessment Box SPM.2 Table 1 (continued)

Continued next page →

Australasia

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Significant change in community composition and structure of coral reef systems in Australia (*high confidence*) [25.6, 30.5, Boxes CC-CR and CC-OA]	• Ability of corals to adapt naturally appears limited and insufficient to offset the detrimental effects of rising temperatures and acidification. • Other options are mostly limited to reducing other stresses (water quality, tourism, fishing) and early warning systems; direct interventions such as assisted colonization and shading have been proposed but remain untested at scale.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (*high confidence*) [Table 25-1, Boxes 25-8 and 25-9]	• Significant adaptation deficit in some regions to current flood risk. • Effective adaptation includes land-use controls and relocation as well as protection and accommodation of increased risk to ensure flexibility.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damage towards the upper end of projected sea-level-rise ranges (*high confidence*) [25.6, 25.10, Box 25-1]	• Adaptation deficit in some locations to current coastal erosion and flood risk. Successive building and protection cycles constrain flexible responses. • Effective adaptation includes land-use controls and ultimately relocation as well as protection and accommodation.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high

North America

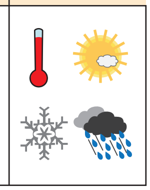
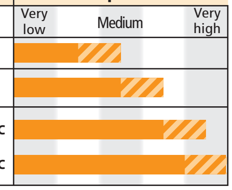
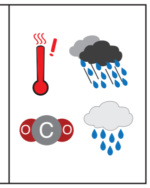
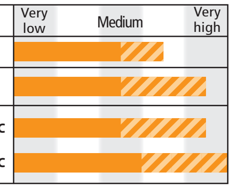
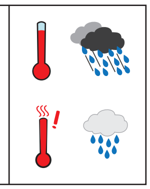
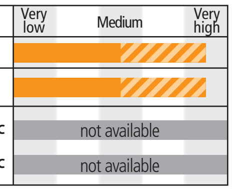
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Wildfire-induced loss of ecosystem integrity, property loss, human morbidity, and mortality as a result of increased drying trend and temperature trend (*high confidence*) [26.4, 26.8, Box 26-2]	• Some ecosystems are more fire-adapted than others. Forest managers and municipal planners are increasingly incorporating fire protection measures (e.g., prescribed burning, introduction of resilient vegetation). Institutional capacity to support ecosystem adaptation is limited. • Adaptation of human settlements is constrained by rapid private property development in high-risk areas and by limited household-level adaptive capacity. • Agroforestry can be an effective strategy for reduction of slash and burn practices in Mexico.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Heat-related human mortality (*high confidence*) [26.6, 26.8]	• Residential air conditioning (A/C) can effectively reduce risk. However, availability and usage of A/C is highly variable and is subject to complete loss during power failures. Vulnerable populations include athletes and outdoor workers for whom A/C is not available. • Community- and household-scale adaptations have the potential to reduce exposure to heat extremes via family support, early heat warning systems, cooling centers, greening, and high-albedo surfaces.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Urban floods in riverine and coastal areas, inducing property and infrastructure damage; supply chain, ecosystem, and social system disruption; public health impacts; and water quality impairment, due to sea level rise, extreme precipitation, and cyclones (*high confidence*) [26.2-4, 26.8]	• Implementing management of urban drainage is expensive and disruptive to urban areas. • Low-regret strategies with co-benefits include less impervious surfaces leading to more groundwater recharge, green infrastructure, and rooftop gardens. • Sea level rise increases water elevations in coastal outfalls, which impedes drainage. In many cases, older rainfall design standards are being used that need to be updated to reflect current climate conditions. • Conservation of wetlands, including mangroves, and land-use planning strategies can reduce the intensity of flood events.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high

SPM

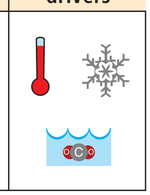
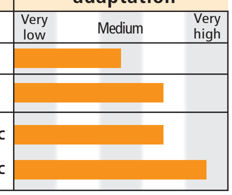
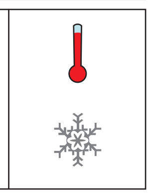
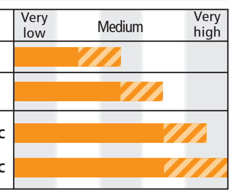
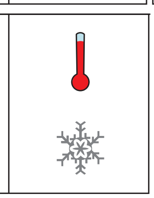
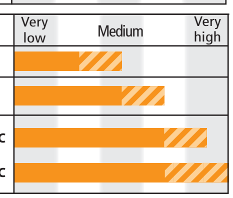
Assessment Box SPM.2 Table 1 (continued)

Continued next page →

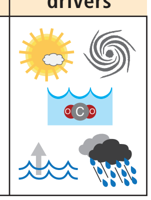
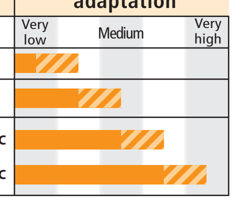
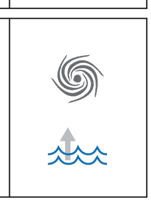
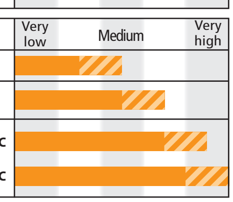
Central and South America

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Water availability in semi-arid and glacier-melt-dependent regions and Central America; flooding and landslides in urban and rural areas due to extreme precipitation (*high confidence*) [27.3]	• Integrated water resource management • Urban and rural flood management (including infrastructure), early warning systems, better weather and runoff forecasts, and infectious disease control		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Decreased food production and food quality (*medium confidence*) [27.3]	• Development of new crop varieties more adapted to climate change (temperature and drought) • Offsetting of human and animal health impacts of reduced food quality • Offsetting of economic impacts of land-use change • Strengthening traditional indigenous knowledge systems and practices		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Spread of vector-borne diseases in altitude and latitude (*high confidence*) [27.3]	• Development of early warning systems for disease control and mitigation based on climatic and other relevant inputs. Many factors augment vulnerability. • Establishing programs to extend basic public health services		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

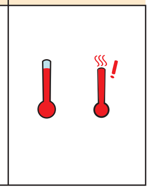
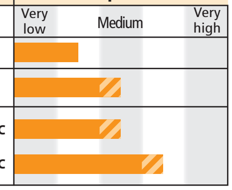
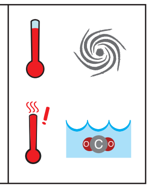
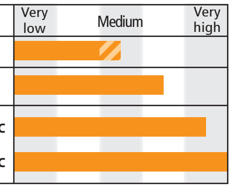
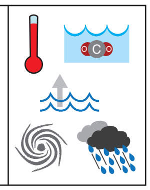
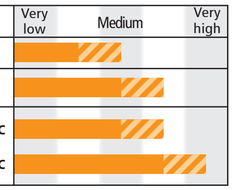
Polar Regions

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Risks for freshwater and terrestrial ecosystems (*high confidence*) and marine ecosystems (*medium confidence*), due to changes in ice, snow cover, permafrost, and freshwater/ocean conditions, affecting species´ habitat quality, ranges, phenology, and productivity, as well as dependent economies [28.2-4]	• Improved understanding through scientific and indigenous knowledge, producing more effective solutions and/or technological innovations • Enhanced monitoring, regulation, and warning systems that achieve safe and sustainable use of ecosystem resources • Hunting or fishing for different species, if possible, and diversifying income sources		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Risks for the health and well-being of Arctic residents, resulting from injuries and illness from the changing physical environment, food insecurity, lack of reliable and safe drinking water, and damage to infrastructure, including infrastructure in permafrost regions (*high confidence*) [28.2-4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Shifting resource bases, land use, and/or settlement areas		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Unprecedented challenges for northern communities due to complex inter-linkages between climate-related hazards and societal factors, particularly if rate of change is faster than social systems can adapt (*high confidence*) [28.2-4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Adaptive co-management responses developed through the settlement of land claims		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

Small Islands

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Loss of livelihoods, coastal settlements, infrastructure, ecosystem services, and economic stability (*high confidence*) [29.6, 29.8, Figure 29-4]	• Significant potential exists for adaptation in islands, but additional external resources and technologies will enhance response. • Maintenance and enhancement of ecosystem functions and services and of water and food security • Efficacy of traditional community coping strategies is expected to be substantially reduced in the future.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
The interaction of rising global mean sea level in the 21st century with high-water-level events will threaten low-lying coastal areas (*high confidence*) [29.4, Table 29-1; WGI AR5 13.5, Table 13.5]	• High ratio of coastal area to land mass will make adaptation a significant financial and resource challenge for islands. • Adaptation options include maintenance and restoration of coastal landforms and ecosystems, improved management of soils and freshwater resources, and appropriate building codes and settlement patterns.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

Assessment Box SPM.2 Table 1 (continued)

The Ocean				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Distributional shift in fish and invertebrate species, and decrease in fisheries catch potential at low latitudes, e.g., in equatorial upwelling and coastal boundary systems and sub-tropical gyres (*high confidence*) [6.3, 30.5-6, Tables 6-6 and 30-3, Box CC-MB]	• Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their changes in distribution to maintain temperatures. • Human adaptation options: Large-scale translocation of industrial fishing activities following the regional decreases (low latitude) vs. possibly transient increases (high latitude) in catch potential; Flexible management that can react to variability and change; Improvement of fish resilience to thermal stress by reducing other stressors such as pollution and eutrophication; Expansion of sustainable aquaculture and the development of alternative livelihoods in some regions.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Reduced biodiversity, fisheries abundance, and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, exacerbated by ocean acidification, e.g., in coastal boundary systems and sub-tropical gyres (*high confidence*) [5.4, 6.4, 30.3, 30.5-6, Tables 6-6 and 30-3, Box CC-CR]	• Evidence of rapid evolution by corals is very limited. Some corals may migrate to higher latitudes, but entire reef systems are not expected to be able to track the high rates of temperature shifts. • Human adaptation options are limited to reducing other stresses, mainly by enhancing water quality, and limiting pressures from tourism and fishing. These options will delay human impacts of climate change by a few decades, but their efficacy will be severely reduced as thermal stress increases.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Coastal inundation and habitat loss due to sea level rise, extreme events, changes in precipitation, and reduced ecological resilience, e.g., in coastal boundary systems and sub-tropical gyres (*medium* to *high confidence*) [5.5, 30.5-6, Tables 6-6 and 30-3, Box CC-CR]	• Human adaptation options are limited to reducing other stresses, mainly by reducing pollution and limiting pressures from tourism, fishing, physical destruction, and unsustainable aquaculture. • Reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients • Increased mangrove, coral reef, and seagrass protection, and restoration to protect numerous ecosystem goods and services such as coastal protection, tourist value, and fish habitat		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

C: MANAGING FUTURE RISKS AND BUILDING RESILIENCE

Managing the risks of climate change involves adaptation and mitigation decisions with implications for future generations, economies, and environments. This section evaluates adaptation as a means to build resilience and to adjust to climate-change impacts. It also considers limits to adaptation, climate-resilient pathways, and the role of transformation. See Figure SPM.8 for an overview of responses for addressing risk related to climate change.

C-1. Principles for Effective Adaptation

Adaptation is place- and context-specific, with no single approach for reducing risks appropriate across all settings (*high confidence*). Effective risk reduction and adaptation strategies consider the dynamics of vulnerability and exposure and their linkages with socioeconomic processes, sustainable development, and climate change. Specific examples of responses to climate change are presented in Table SPM.1.[67]

Adaptation planning and implementation can be enhanced through complementary actions across levels, from individuals to governments (*high confidence*). National governments can coordinate adaptation efforts of local and subnational governments, for example by protecting vulnerable groups, by supporting economic diversification, and by providing information, policy and legal frameworks, and financial support (*robust evidence*, *high agreement*). Local government and the private sector are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households, and civil society and in managing risk information and financing (*medium evidence*, *high agreement*).[68]

A first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate variability (*high confidence*). Strategies include actions with co-benefits for other objectives. Available strategies and actions can increase resilience across a range of possible future climates while helping to improve human health, livelihoods, social and economic well-being, and

[67] 2.1, 8.3-4, 13.1, 13.3-4, 15.2-3, 15.5, 16.2-3, 16.5, 17.2, 17.4, 19.6, 21.3, 22.4, 26.8-9, 29.6, 29.8

[68] 2.1-4, 3.6, 5.5, 8.3-4, 9.3-4, 14.2, 15.2-3, 15.5, 16.2-5, 17.2-3, 22.4, 24.4, 25.4, 26.8-9, 30.7, Tables 21-1, 21-5, & 21-6, Box 16-2

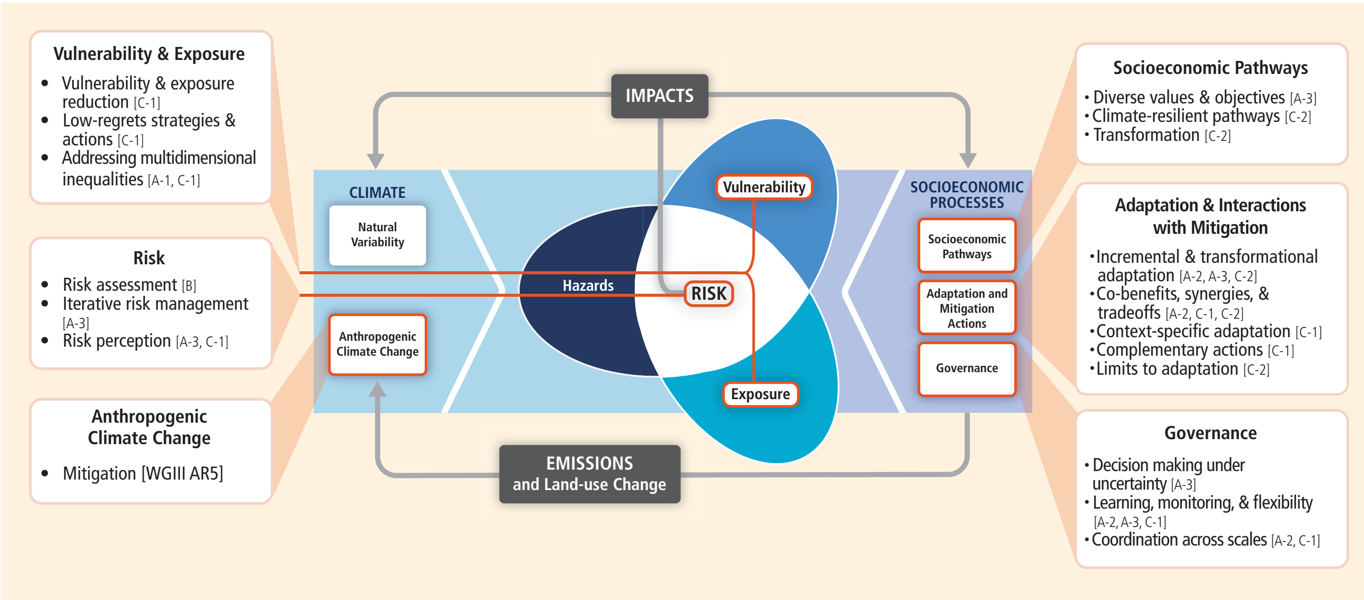


Figure SPM.8 | The solution space. Core concepts of the WGII AR5, illustrating overlapping entry points and approaches, as well as key considerations, in managing risks related to climate change, as assessed in this report and presented throughout this SPM. Bracketed references indicate sections of this summary with corresponding assessment findings.

environmental quality. See Table SPM.1. Integration of adaptation into planning and decision making can promote synergies with development and disaster risk reduction.[69]

Adaptation planning and implementation at all levels of governance are contingent on societal values, objectives, and risk perceptions (*high confidence*). Recognition of diverse interests, circumstances, social-cultural contexts, and expectations can benefit decision-making processes. Indigenous, local, and traditional knowledge systems and practices, including indigenous peoples' holistic view of community and environment, are a major resource for adapting to climate change, but these have not been used consistently in existing adaptation efforts. Integrating such forms of knowledge with existing practices increases the effectiveness of adaptation.[70]

Decision support is most effective when it is sensitive to context and the diversity of decision types, decision processes, and constituencies (*robust evidence*, *high agreement*). Organizations bridging science and decision making, including climate services, play an important role in the communication, transfer, and development of climate-related knowledge, including translation, engagement, and knowledge exchange (*medium evidence*, *high agreement*).[71]

Existing and emerging economic instruments can foster adaptation by providing incentives for anticipating and reducing impacts (*medium confidence*). Instruments include public-private finance partnerships, loans, payments for environmental services, improved resource pricing, charges and subsidies, norms and regulations, and risk sharing and transfer mechanisms. Risk financing mechanisms in the public and private sector, such as insurance and risk pools, can contribute to increasing resilience, but without attention to major design challenges, they can also provide disincentives, cause market failure, and decrease equity. Governments often play key roles as regulators, providers, or insurers of last resort.[72]

Constraints can interact to impede adaptation planning and implementation (*high confidence*). Common constraints on implementation arise from the following: limited financial and human resources; limited integration or coordination of governance; uncertainties

[69] 3.6, 8.3, 9.4, 14.3, 15.2-3, 17.2, 20.4, 20.6, 22.4, 24.4-5, 25.4, 25.10, 27.3-5, 29.6, Boxes 25-2 and 25-6
[70] 2.2-4, 9.4, 12.3, 13.2, 15.2, 16.2-4, 16.7, 17.2-3, 21.3, 22.4, 24.4, 24.6, 25.4, 25.8, 26.9, 28.2, 28.4, Table 15-1, Box 25-7
[71] 2.1-4, 8.4, 14.4, 16.2-3, 16.5, 21.2-3, 21.5, 22.4, Box 9-4
[72] 10.7, 10.9, 13.3, 17.4-5, Box 25-7

Table SPM.1 | Approaches for managing the risks of climate change. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Mitigation is considered essential for managing the risks of climate change. It is not addressed in this table as mitigation is the focus of WGIII AR5. Examples are presented in no specific order and can be relevant to more than one category. [14.2-3, Table 14-1]

Overlapping Approaches	Category	Examples	Chapter Reference(s)
Vulnerability & Exposure Reduction through development, planning, & practices including many low-regrets measures	Human development	Improved access to education, nutrition, health facilities, energy, safe housing & settlement structures, & social support structures; Reduced gender inequality & marginalization in other forms.	8.3, 9.3, 13.1-3, 14.2-3, 22.4
	Poverty alleviation	Improved access to & control of local resources; Land tenure; Disaster risk reduction; Social safety nets & social protection; Insurance schemes.	8.3-4, 9.3, 13.1-3
	Livelihood security	Income, asset, & livelihood diversification; Improved infrastructure; Access to technology & decision-making fora; Increased decision-making power; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	7.5, 9.4, 13.1-3, 22.3-4, 23.4, 26.5, 27.3, 29.6, Table SM24-7
	Disaster risk management	Early warning systems; Hazard & vulnerability mapping; Diversifying water resources; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements.	8.2-4, 11.7, 14.3, 15.4, 22.4, 24.4, 26.6, 28.4, Box 25-1, Table 3-3
	Ecosystem management	Maintaining wetlands & urban green spaces; Coastal afforestation; Watershed & reservoir management; Reduction of other stressors on ecosystems & of habitat fragmentation; Maintenance of genetic diversity; Manipulation of disturbance regimes; Community-based natural resource management.	4.3-4, 8.3, 22.4, Table 3-3, Boxes 4-3, 8-2, 15-1, 25-8, 25-9, & CC-EA
	Spatial or land-use planning	Provisioning of adequate housing, infrastructure, & services; Managing development in flood prone & other high risk areas; Urban planning & upgrading programs; Land zoning laws; Easements; Protected areas.	4.4, 8.1-4, 22.4, 23.7-8, 27.3, Box 25-8
Adaptation including incremental & transformational adjustments	Structural/physical	***Engineered & built-environment options***: Sea walls & coastal protection structures; Flood levees; Water storage; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements; Floating houses; Power plant & electricity grid adjustments.	3.5-6, 5.5, 8.2-3, 10.2, 11.7, 23.3, 24.4, 25.7, 26.3, 26.8, Boxes 15-1, 25-1, 25-2, & 25-8
		Technological options: New crop & animal varieties; Indigenous, traditional, & local knowledge, technologies, & methods; Efficient irrigation; Water-saving technologies; Desalinization; Conservation agriculture; Food storage & preservation facilities; Hazard & vulnerability mapping & monitoring; Early warning systems; Building insulation; Mechanical & passive cooling; Technology development, transfer, & diffusion.	7.5, 8.3, 9.4, 10.3, 15.4, 22.4, 24.4, 26.3, 26.5, 27.3, 28.2, 28.4, 29.6-7, Boxes 20-5 & 25-2, Tables 3-3 & 15-1
		Ecosystem-based options: Ecological restoration; Soil conservation; Afforestation & reforestation; Mangrove conservation & replanting; Green infrastructure (e.g., shade trees, green roofs); Controlling overfishing; Fisheries co-management; Assisted species migration & dispersal; Ecological corridors; Seed banks, gene banks, & other *ex situ* conservation; Community-based natural resource management.	4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 15.4, 22.4, 23.6-7, 24.4, 25.6, 27.3, 28.2, 29.7, 30.6, Boxes 15-1, 22-2, 25-9, 26-2, & CC-EA
		Services: Social safety nets & social protection; Food banks & distribution of food surplus; Municipal services including water & sanitation; Vaccination programs; Essential public health services; Enhanced emergency medical services.	3.5-6, 8.3, 9.3, 11.7, 11.9, 22.4, 29.6, Box 13-2
	Institutional	***Economic options***: Financial incentives; Insurance; Catastrophe bonds; Payments for ecosystem services; Pricing water to encourage universal provision and careful use; Microfinance; Disaster contingency funds; Cash transfers; Public-private partnerships.	8.3-4, 9.4, 10.7, 11.7, 13.3, 15.4, 17.5, 22.4, 26.7, 27.6, 29.6, Box 25-7
		Laws & regulations: Land zoning laws; Building standards & practices; Easements; Water regulations & agreements; Laws to support disaster risk reduction; Laws to encourage insurance purchasing; Defined property rights & land tenure security; Protected areas; Fishing quotas; Patent pools & technology transfer.	4.4, 8.3, 9.3, 10.5, 10.7, 15.2, 15.4, 17.5, 22.4, 23.4, 23.7, 24.4, 25.4, 26.3, 27.3, 30.6, Table 25-2, Box CC-CR
		National & government policies & programs: National & regional adaptation plans including mainstreaming; Sub-national & local adaptation plans; Economic diversification; Urban upgrading programs; Municipal water management programs; Disaster planning & preparedness; Integrated water resource management; Integrated coastal zone management; Ecosystem-based management; Community-based adaptation.	2.4, 3.6, 4.4, 5.5, 6.4, 7.5, 8.3, 11.7, 15.2-5, 22.4, 23.7, 25.4, 25.8, 26.8-9, 27.3-4, 29.6, Boxes 25-1, 25-2, & 25-9, Tables 9-2 & 17-1
	Social	***Educational options***: Awareness raising & integrating into education; Gender equity in education; Extension services; Sharing indigenous, traditional, & local knowledge; Participatory action research & social learning; Knowledge-sharing & learning platforms.	8.3-4, 9.4, 11.7, 12.3, 15.2-4, 22.4, 25.4, 28.4, 29.6, Tables 15-1 & 25-2
		Informational options: Hazard & vulnerability mapping; Early warning & response systems; Systematic monitoring & remote sensing; Climate services; Use of indigenous climate observations; Participatory scenario development; Integrated assessments.	2.4, 5.5, 8.3-4, 9.4, 11.7, 15.2-4, 22.4, 23.5, 24.4, 25.8, 26.6, 26.8, 27.3, 28.2, 28.5, 30.6, Table 25-2, Box 26-3
		Behavioral options: Household preparation & evacuation planning; Migration; Soil & water conservation; Storm drain clearance; Livelihood diversification; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	5.5, 7.5, 9.4, 12.4, 22.3-4, 23.4, 23.7, 25.7, 26.5, 27.3, 29.6, Table SM24-7, Box 25-5
Transformation	Spheres of change	***Practical***: Social & technical innovations, behavioral shifts, or institutional & managerial changes that produce substantial shifts in outcomes.	8.3, 17.3, 20.5, Box 25-5
		Political: Political, social, cultural, & ecological decisions & actions consistent with reducing vulnerability & risk & supporting adaptation, mitigation, & sustainable development.	14.2-3, 20.5, 25.4, 30.7, Table 14-1
		Personal: Individual & collective assumptions, beliefs, values, & worldviews influencing climate-change responses.	14.2-3, 20.5, 25.4, Table 14-1

about projected impacts; different perceptions of risks; competing values; absence of key adaptation leaders and advocates; and limited tools to monitor adaptation effectiveness. Another constraint includes insufficient research, monitoring, and observation and the finance to maintain them. Underestimating the complexity of adaptation as a social process can create unrealistic expectations about achieving intended adaptation outcomes.[73]

Poor planning, overemphasizing short-term outcomes, or failing to sufficiently anticipate consequences can result in maladaptation (*medium evidence*, *high agreement*). Maladaptation can increase the vulnerability or exposure of the target group in the future, or the vulnerability of other people, places, or sectors. Some near-term responses to increasing risks related to climate change may also limit future choices. For example, enhanced protection of exposed assets can lock in dependence on further protection measures.[74]

Limited evidence indicates a gap between global adaptation needs and the funds available for adaptation (*medium confidence*). There is a need for a better assessment of global adaptation costs, funding, and investment. Studies estimating the global cost of adaptation are characterized by shortcomings in data, methods, and coverage (*high confidence*).[75]

Significant co-benefits, synergies, and trade-offs exist between mitigation and adaptation and among different adaptation responses; interactions occur both within and across regions (*very high confidence*). Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use, and biodiversity, but tools to understand and manage these interactions remain limited. Examples of actions with co-benefits include (i) improved energy efficiency and cleaner energy sources, leading to reduced emissions of health-damaging climate-altering air pollutants; (ii) reduced energy and water consumption in urban areas through greening cities and recycling water; (iii) sustainable agriculture and forestry; and (iv) protection of ecosystems for carbon storage and other ecosystem services.[76]

C-2. Climate-resilient Pathways and Transformation

Climate-resilient pathways are sustainable-development trajectories that combine adaptation and mitigation to reduce climate change and its impacts. They include iterative processes to ensure that effective risk management can be implemented and sustained. See Figure SPM.9.[77]

Prospects for climate-resilient pathways for sustainable development are related fundamentally to what the world accomplishes with climate-change mitigation (*high confidence*). Since mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades. Delaying mitigation actions may reduce options for climate-resilient pathways in the future.[78]

Greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*). Limits to adaptation occur when adaptive actions to avoid intolerable risks for an actor's objectives or for the needs of a system are not possible or are not currently available. Value-based judgments of what constitutes an intolerable risk may differ. Limits to adaptation emerge from the interaction among climate change and biophysical and/or socioeconomic constraints. Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if limits to adaptation are exceeded. In some parts of the world, insufficient responses to emerging impacts are already eroding the basis for sustainable development.[79]

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[73] 3.6, 4.4, 5.5, 8.4, 9.4, 13.2-3, 14.2, 14.5, 15.2-3, 15.5, 16.2-3, 16.5, 17.2-3, 22.4, 23.7, 24.5, 25.4, 25.10, 26.8-9, 30.6, Table 16-3, Boxes 16-1 and 16-3
[74] 5.5, 8.4, 14.6, 15.5, 16.3, 17.2-3, 20.2, 22.4, 24.4, 25.10, 26.8, Table 14-4, Box 25-1
[75] 14.2, 17.4, Tables 17-2 and 17-3
[76] 2.4-5, 3.7, 4.2, 4.4, 5.4-5, 8.4, 9.3, 11.9, 13.3, 17.2, 19.3-4, 20.2-5, 21.4, 22.6, 23.8, 24.6, 25.6-7, 25.9, 26.8-9, 27.3, 29.6-8, Boxes 25-2, 25-9, 25-10, 30.6-7, CC-WE, and CC-RF
[77] 2.5, 20.3-4
[78] 1.1, 19.7, 20.2-3, 20.6, Figure 1-5
[79] 1.1, 11.8, 13.4, 16.2-7, 17.2, 20.2-3, 20.5-6, 25.10, 26.5, Boxes 16-1, 16-3, and 16-4

Transformations in economic, social, technological, and political decisions and actions can enable climate-resilient pathways (*high confidence*). Specific examples are presented in Table SPM.1. Strategies and actions can be pursued now that will move towards climate-resilient pathways for sustainable development, while at the same time helping to improve livelihoods, social and economic well-being, and responsible environmental management. At the national level, transformation is considered most effective when it reflects a country's own visions and approaches to achieving sustainable development in accordance with its national circumstances and priorities. Transformations to sustainability are considered to benefit from iterative learning, deliberative processes, and innovation.[80]

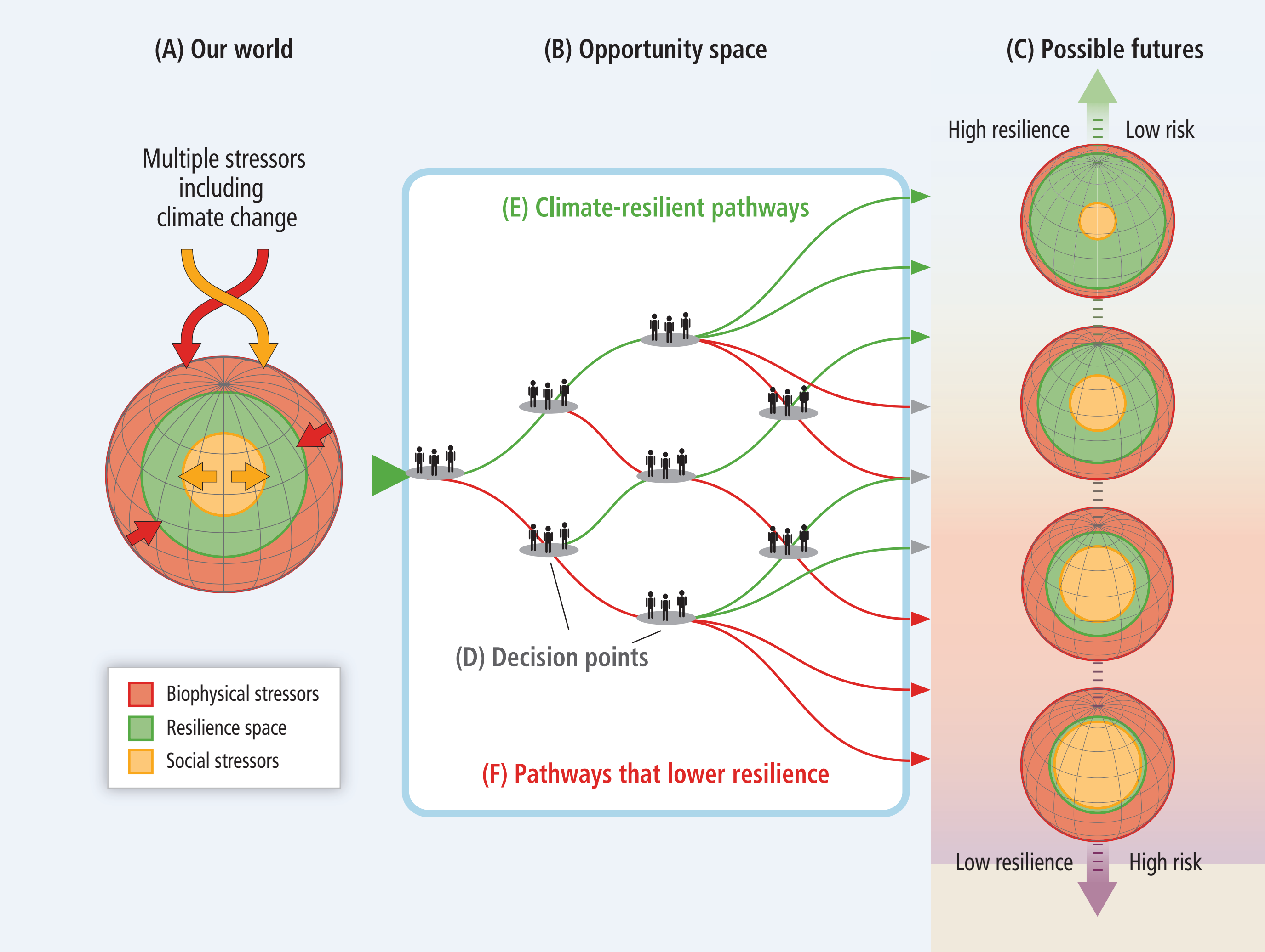

Figure SPM.9 | Opportunity space and climate-resilient pathways. (A) Our world [Sections A-1 and B-1] is threatened by multiple stressors that impinge on resilience from many directions, represented here simply as biophysical and social stressors. Stressors include climate change, climate variability, land-use change, degradation of ecosystems, poverty and inequality, and cultural factors. (B) Opportunity space [Sections A-2, A-3, B-2, C-1, and C-2] refers to decision points and pathways that lead to a range of (C) possible futures [Sections C and B-3] with differing levels of resilience and risk. (D) Decision points result in actions or failures-to-act throughout the opportunity space, and together they constitute the process of managing or failing to manage risks related to climate change. (E) Climate-resilient pathways (in green) within the opportunity space lead to a more resilient world through adaptive learning, increasing scientific knowledge, effective adaptation and mitigation measures, and other choices that reduce risks. (F) Pathways that lower resilience (in red) can involve insufficient mitigation, maladaptation, failure to learn and use knowledge, and other actions that lower resilience; and they can be irreversible in terms of possible futures.

[80] 1.1, 2.1, 2.5, 8.4, 14.1, 14.3, 16.2-7, 20.5, 22.4, 25.4, 25.10, Figure 1-5, Boxes 16-1, 16-4, and TS.8

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SUPPLEMENTARY MATERIAL

Table SPM.A1 | Observed impacts attributed to climate change reported in the scientific literature since the AR4. These impacts have been attributed to climate change with *very low*, *low*, *medium*, or *high confidence*, with the relative contribution of climate change to the observed change indicated (major or minor), for natural and human systems across eight major world regions over the past several decades. [Tables 18-5, 18-6, 18-7, 18-8, and 18-9] Absence from the table of additional impacts attributed to climate change does not imply that such impacts have not occurred.

	Africa
Snow & Ice, Rivers & Lakes, Floods & Drought	• Retreat of tropical highland glaciers in East Africa (*high confidence*, major contribution from climate change) • Reduced discharge in West African rivers (*low confidence*, major contribution from climate change) • Lake surface warming and water column stratification increases in the Great Lakes and Lake Kariba (*high confidence*, major contribution from climate change) • Increased soil moisture drought in the Sahel since 1970, partially wetter conditions since 1990 (*medium confidence*, major contribution from climate change) [22.2-3, Tables 18-5, 18-6, and 22-3]
Terrestrial Ecosystems	• Tree density decreases in western Sahel and semi-arid Morocco, beyond changes due to land use (*medium confidence*, major contribution from climate change) • Range shifts of several southern plants and animals, beyond changes due to land use (*medium confidence*, major contribution from climate change) • Increases in wildfires on Mt. Kilimanjaro (*low confidence*, major contribution from climate change) [22.3, Tables 18-7 and 22-3]
Coastal Erosion & Marine Ecosystems	• Decline in coral reefs in tropical African waters, beyond decline due to human impacts (*high confidence*, major contribution from climate change) [Table 18-8]
Food Production & Livelihoods	• Adaptive responses to changing rainfall by South African farmers, beyond changes due to economic conditions (*very low confidence*, major contribution from climate change) • Decline in fruit-bearing trees in Sahel (*low confidence*, major contribution from climate change) • Malaria increases in Kenyan highlands, beyond changes due to vaccination, drug resistance, demography, and livelihoods (*low confidence*, minor contribution from climate change) • Reduced fisheries productivity of Great Lakes and Lake Kariba, beyond changes due to fisheries management and land use (*low confidence*, minor contribution from climate change) [7.2, 11.5, 13.2, 22.3, Table 18-9]
	Europe
Snow & Ice, Rivers & Lakes, Floods & Drought	• Retreat of Alpine, Scandinavian, and Icelandic glaciers (*high confidence*, major contribution from climate change) • Increase in rock slope failures in western Alps (*medium confidence*, major contribution from climate change) • Changed occurrence of extreme river discharges and floods (*very low confidence*, minor contribution from climate change) [18.3, 23.2-3, Tables 18-5 and 18-6; WGI AR5 4.3]
Terrestrial Ecosystems	• Earlier greening, leaf emergence, and fruiting in temperate and boreal trees (*high confidence*, major contribution from climate change) • Increased colonization of alien plant species in Europe, beyond a baseline of some invasion (*medium confidence*, major contribution from climate change) • Earlier arrival of migratory birds in Europe since 1970 (*medium confidence*, major contribution from climate change) • Upward shift in tree-line in Europe, beyond changes due to land use (*low confidence*, major contribution from climate change) • Increasing burnt forest areas during recent decades in Portugal and Greece, beyond some increase due to land use (*high confidence*, major contribution from climate change) [4.3, 18.3, Tables 18-7 and 23-6]
Coastal Erosion & Marine Ecosystems	• Northward distributional shifts of zooplankton, fishes, seabirds, and benthic invertebrates in northeast Atlantic (*high confidence*, major contribution from climate change) • Northward and depth shift in distribution of many fish species across European seas (*medium confidence*, major contribution from climate change) • Plankton phenology changes in northeast Atlantic (*medium confidence*, major contribution from climate change) • Spread of warm water species into the Mediterranean, beyond changes due to invasive species and human impacts (*medium confidence*, major contribution from climate change) [6.3, 23.6, 30.5, Tables 6-2 and 18-8, Boxes 6-1 and CC-MB]
Food Production & Livelihoods	• Shift from cold-related mortality to heat-related mortality in England and Wales, beyond changes due to exposure and health care (*low confidence*, major contribution from climate change) • Impacts on livelihoods of Sámi people in northern Europe, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) • Stagnation of wheat yields in some countries in recent decades, despite improved technology (*medium confidence*, minor contribution from climate change) • Positive yield impacts for some crops mainly in northern Europe, beyond increase due to improved technology (*medium confidence*, minor contribution from climate change) • Spread of bluetongue virus in sheep and of ticks across parts of Europe (*medium confidence*, minor contribution from climate change) [18.4, 23.4-5, Table 18-9, Figure 7-2]

Continued next page →

Table SPM.A1 (continued)

Asia	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Permafrost degradation in Siberia, Central Asia, and Tibetan Plateau (*high confidence*, major contribution from climate change) • Shrinking mountain glaciers across most of Asia (*medium confidence*, major contribution from climate change) • Changed water availability in many Chinese rivers, beyond changes due to land use (*low confidence*, minor contribution from climate change) • Increased flow in several rivers due to shrinking glaciers (*high confidence*, major contribution from climate change) • Earlier timing of maximum spring flood in Russian rivers (*medium confidence*, major contribution from climate change) • Reduced soil moisture in north-central and northeast China (1950–2006) (*medium confidence*, major contribution from climate change) • Surface water degradation in parts of Asia, beyond changes due to land use (*medium confidence*, minor contribution from climate change) [24.3-4, 28.2, Tables 18-5, 18-6, and SM24-4, Box 3-1; WGI AR5 4.3, 10.5]
Terrestrial Ecosystems	• Changes in plant phenology and growth in many parts of Asia (earlier greening), particularly in the north and east (*medium confidence*, major contribution from climate change) • Distribution shifts of many plant and animal species upwards in elevation or polewards, particularly in the north of Asia (*medium confidence*, major contribution from climate change) • Invasion of Siberian larch forests by pine and spruce during recent decades (*low confidence*, major contribution from climate change) • Advance of shrubs into the Siberian tundra (*high confidence*, major contribution from climate change) [4.3, 24.4, 28.2, Table 18-7, Figure 4-4]
Coastal Erosion & Marine Ecosystems	• Decline in coral reefs in tropical Asian waters, beyond decline due to human impacts (*high confidence*, major contribution from climate change) • Northward range extension of corals in the East China Sea and western Pacific, and of a predatory fish in the Sea of Japan (*medium confidence*, major contribution from climate change) • Shift from sardines to anchovies in the western North Pacific, beyond fluctuations due to fisheries (*low confidence*, major contribution from climate change) • Increased coastal erosion in Arctic Asia (*low confidence*, major contribution from climate change) [6.3, 24.4, 30.5, Tables 6-2 and 18-8]
Food Production & Livelihoods	• Impacts on livelihoods of indigenous groups in Arctic Russia, beyond economic and sociopolitical changes (*low confidence*, major contribution from climate change) • Negative impacts on aggregate wheat yields in South Asia, beyond increase due to improved technology (*medium confidence*, minor contribution from climate change) • Negative impacts on aggregate wheat and maize yields in China, beyond increase due to improved technology (*low confidence*, minor contribution from climate change) • Increases in a water-borne disease in Israel (*low confidence*, minor contribution from climate change) [7.2, 13.2, 18.4, 28.2, Tables 18-4 and 18-9, Figure 7-2]
Australasia	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Significant decline in late-season snow depth at 3 of 4 alpine sites in Australia (1957–2002) (*medium confidence*, major contribution from climate change) • Substantial reduction in ice and glacier ice volume in New Zealand (*medium confidence*, major contribution from climate change) • Intensification of hydrological drought due to regional warming in southeast Australia (*low confidence*, minor contribution from climate change) • Reduced inflow in river systems in southwestern Australia (since the mid-1970s) (*high confidence*, major contribution from climate change) [25.5, Tables 18-5, 18-6, and 25-1; WGI AR5 4.3]
Terrestrial Ecosystems	• Changes in genetics, growth, distribution, and phenology of many species, in particular birds, butterflies, and plants in Australia, beyond fluctuations due to variable local climates, land use, pollution, and invasive species (*high confidence*, major contribution from climate change) • Expansion of some wetlands and contraction of adjacent woodlands in southeast Australia (*low confidence*, major contribution from climate change) • Expansion of monsoon rainforest at expense of savannah and grasslands in northern Australia (*medium confidence*, major contribution from climate change) • Migration of glass eels advanced by several weeks in Waikato River, New Zealand (*low confidence*, major contribution from climate change) [Tables 18-7 and 25-3]
Coastal Erosion & Marine Ecosystems	• Southward shifts in the distribution of marine species near Australia, beyond changes due to short-term environmental fluctuations, fishing, and pollution (*medium confidence*, major contribution from climate change) • Change in timing of migration of seabirds in Australia (*low confidence*, major contribution from climate change) • Increased coral bleaching in Great Barrier Reef and western Australian reefs, beyond effects from pollution and physical disturbance (*high confidence*, major contribution from climate change) • Changed coral disease patterns at Great Barrier Reef, beyond effects from pollution (*medium confidence*, major contribution from climate change) [6.3, 25.6, Tables 18-8 and 25-3]
Food Production & Livelihoods	• Advanced timing of wine-grape maturation in recent decades, beyond advance due to improved management (*medium confidence*, major contribution from climate change) • Shift in winter vs. summer human mortality in Australia, beyond changes due to exposure and health care (*low confidence*, major contribution from climate change) • Relocation or diversification of agricultural activities in Australia, beyond changes due to policy, markets, and short-term climate variability (*low confidence*, minor contribution from climate change) [11.4, 18.4, 25.7-8, Tables 18-9 and 25-3, Box 25-5]
North America	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Shrinkage of glaciers across western and northern North America (*high confidence*, major contribution from climate change) • Decreasing amount of water in spring snowpack in western North America (1960–2002) (*high confidence*, major contribution from climate change) • Shift to earlier peak flow in snow dominated rivers in western North America (*high confidence*, major contribution from climate change) • Increased runoff in the midwestern and northeastern US (*medium confidence*, minor contribution from climate change) [Tables 18-5 and 18-6; WGI AR5 2.6, 4.3]
Terrestrial Ecosystems	• Phenology changes and species distribution shifts upward in elevation and northward across multiple taxa (*medium confidence*, major contribution from climate change) • Increased wildfire frequency in subarctic conifer forests and tundra (*medium confidence*, major contribution from climate change) • Regional increases in tree mortality and insect infestations in forests (*low confidence*, minor contribution from climate change) • Increase in wildfire activity, fire frequency and duration, and burnt area in forests of the western US and boreal forests in Canada, beyond changes due to land use and fire management (*medium confidence*, minor contribution from climate change) [26.4, 28.2, Table 18-7, Box 26-2]
Coastal Erosion & Marine Ecosystems	• Northward distributional shifts of northwest Atlantic fish species (*high confidence*, major contribution from climate change) • Changes in musselbeds along the west coast of US (*high confidence*, major contribution from climate change) • Changed migration and survival of salmon in northeast Pacific (*high confidence*, major contribution from climate change) • Increased coastal erosion in Alaska and Canada (*medium confidence*, major contribution from climate change) [18.3, 30.5, Tables 6-2 and 18-8]
Food Production & Livelihoods	• Impacts on livelihoods of indigenous groups in the Canadian Arctic, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) [18.4, 28.2, Tables 18-4 and 18-9]

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Table SPM.A1 (continued)

Central and South America	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Shrinkage of Andean glaciers (*high confidence*, major contribution from climate change) • Changes in extreme flows in Amazon River (*medium confidence*, major contribution from climate change) • Changing discharge patterns in rivers in the western Andes (*medium confidence*, major contribution from climate change) • Increased streamflow in sub-basins of the La Plata River, beyond increase due to land-use change (*high confidence*, major contribution from climate change) [27.3, Tables 18-5, 18-6, and 27-3; WGI AR5 4.3]
Terrestrial Ecosystems	• Increased tree mortality and forest fire in the Amazon (*low confidence*, minor contribution from climate change) • Rainforest degradation and recession in the Amazon, beyond reference trends in deforestation and land degradation (*low confidence*, minor contribution from climate change) [4.3, 18.3, 27.2-3, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coral bleaching in western Caribbean, beyond effects from pollution and physical disturbance (*high confidence*, major contribution from climate change) • Mangrove degradation on north coast of South America, beyond degradation due to pollution and land use (*low confidence*, minor contribution from climate change) [27.3, Table 18-8]
Food Production & Livelihoods	• More vulnerable livelihood trajectories for indigenous Aymara farmers in Bolivia due to water shortage, beyond effects of increasing social and economic stress (*medium confidence*, major contribution from climate change) • Increase in agricultural yields and expansion of agricultural areas in southeastern South America, beyond increase due to improved technology (*medium confidence*, major contribution from climate change) [13.1, 27.3, Table 18-9]
Polar Regions	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Decreasing Arctic sea ice cover in summer (*high confidence*, major contribution from climate change) • Reduction in ice volume in Arctic glaciers (*high confidence*, major contribution from climate change) • Decreasing snow cover extent across the Arctic (*medium confidence*, major contribution from climate change) • Widespread permafrost degradation, especially in the southern Arctic (*high confidence*, major contribution from climate change) • Ice mass loss along coastal Antarctica (*medium confidence*, major contribution from climate change) • Increased river discharge for large circumpolar rivers (1997–2007) (*low confidence*, major contribution from climate change) • Increased winter minimum river flow in most of the Arctic (*medium confidence*, major contribution from climate change) • Increased lake water temperatures 1985–2009 and prolonged ice-free seasons (*medium confidence*, major contribution from climate change) • Disappearance of thermokarst lakes due to permafrost degradation in the low Arctic. New lakes created in areas of formerly frozen peat (*high confidence*, major contribution from climate change) [28.2, Tables 18-5 and 18-6; WGI AR5 4.2-4, 4.6, 10.5]
Terrestrial Ecosystems	• Increased shrub cover in tundra in North America and Eurasia (*high confidence*, major contribution from climate change) • Advance of Arctic tree-line in latitude and altitude (*medium confidence*, major contribution from climate change) • Changed breeding area and population size of subarctic birds, due to snowbed reduction and/or tundra shrub encroachment (*medium confidence*, major contribution from climate change) • Loss of snow-bed ecosystems and tussock tundra (*high confidence*, major contribution from climate change) • Impacts on tundra animals from increased ice layers in snow pack, following rain-on-snow events (*medium confidence*, major contribution from climate change) • Increased plant species ranges in the West Antarctic Peninsula and nearby islands over the past 50 years (*high confidence*, major contribution from climate change) • Increased phytoplankton productivity in Signy Island lake waters (*high confidence*, major contribution from climate change) [28.2, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coastal erosion across Arctic (*medium confidence*, major contribution from climate change) • Negative effects on non-migratory Arctic species (*high confidence*, major contribution from climate change) • Decreased reproductive success in Arctic seabirds (*medium confidence*, major contribution from climate change) • Decline in Southern Ocean seals and seabirds (*medium confidence*, major contribution from climate change) • Reduced thickness of foraminiferal shells in southern oceans, due to ocean acidification (*medium confidence*, major contribution from climate change) • Reduced krill density in Scotia Sea (*medium confidence*, major contribution from climate change) [6.3, 18.3, 28.2-3, Table 18-8]
Food Production & Livelihoods	• Impact on livelihoods of Arctic indigenous peoples, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) • Increased shipping traffic across the Bering Strait (*medium confidence*, major contribution from climate change) [18.4, 28.2, Tables 18-4 and 18-9, Figure 28-4]
Small Islands	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Increased water scarcity in Jamaica, beyond increase due to water use (*very low confidence*, minor contribution from climate change) [Table 18-6]
Terrestrial Ecosystems	• Tropical bird population changes in Mauritius (*medium confidence*, major contribution from climate change) • Decline of an endemic plant in Hawai'i (*medium confidence*, major contribution from climate change) • Upward trend in tree-lines and associated fauna on high-elevation islands (*low confidence*, minor contribution from climate change) [29.3, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coral bleaching near many tropical small islands, beyond effects of degradation due to fishing and pollution (*high confidence*, major contribution from climate change) • Degradation of mangroves, wetlands, and seagrass around small islands, beyond degradation due to other disturbances (*very low confidence*, minor contribution from climate change) • Increased flooding and erosion, beyond erosion due to human activities, natural erosion, and accretion (*low confidence*, minor contribution from climate change) • Degradation of groundwater and freshwater ecosystems due to saline intrusion, beyond degradation due to pollution and groundwater pumping (*low confidence*, minor contribution from climate change) [29.3, Table 18-8]
Food Production & Livelihoods	• Increased degradation of coastal fisheries due to direct effects and effects of increased coral reef bleaching, beyond degradation due to overfishing and pollution (*low confidence*, minor contribution from climate change) [18.3-4, 29.3, 30.6, Table 18-9, Box CC-CR]

Technical Summary

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Technical Summary

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ASSESSING AND MANAGING THE RISKS OF CLIMATE CHANGE

Human interference with the climate system is occurring (WGI AR5 SPM Section D.3; WGI AR5 Sections 2.2, 6.3, 10.3 to 10.6, 10.9). Climate change poses risks for human and natural systems (Figure TS.1). The assessment of impacts, adaptation, and vulnerability in the Working Group II contribution to the IPCC's Fifth Assessment Report (WGII AR5) evaluates how patterns of risks and potential benefits are shifting due to climate change. It considers how impacts and risks related to climate change can be reduced and managed through adaptation and mitigation. The report assesses needs, options, opportunities, constraints, resilience, limits, and other aspects associated with adaptation. It recognizes that risks of climate change will vary across regions and populations, through space and time, dependent on myriad factors including the extent of adaptation and mitigation.

Climate change involves complex interactions and changing likelihoods of diverse impacts. A focus on risk, which is new in this report, supports decision making in the context of climate change and complements other elements of the report. People and societies may perceive or rank risks and potential benefits differently, given diverse values and goals.

Compared to past WGII reports, the WGII AR5 assesses a substantially larger knowledge base of relevant scientific, technical, and socioeconomic literature. Increased literature has facilitated comprehensive assessment across a broader set of topics and sectors, with expanded coverage of human systems, adaptation, and the ocean. See Box TS.1.

Section A of this summary characterizes observed impacts, vulnerability and exposure, and adaptive responses to date. Section B examines future risks and potential benefits across sectors and regions, highlighting where choices matter for reducing risks through mitigation and adaptation. Section C considers principles for effective adaptation and the broader interactions among adaptation, mitigation, and sustainable development.

Box TS.2 defines central concepts. To convey the degree of certainty in key findings, the report relies on the consistent use of calibrated uncertainty language, introduced in Box TS.3. Chapter references in brackets indicate support for findings, figures, and tables in this summary.

A: OBSERVED IMPACTS, VULNERABILITY, AND ADAPTATION IN A COMPLEX AND CHANGING WORLD

This section presents observed effects of climate change, building from understanding of vulnerability, exposure, and climate-related hazards as determinants of impacts. The section considers the factors, including development and non-climatic stressors, that influence vulnerability and

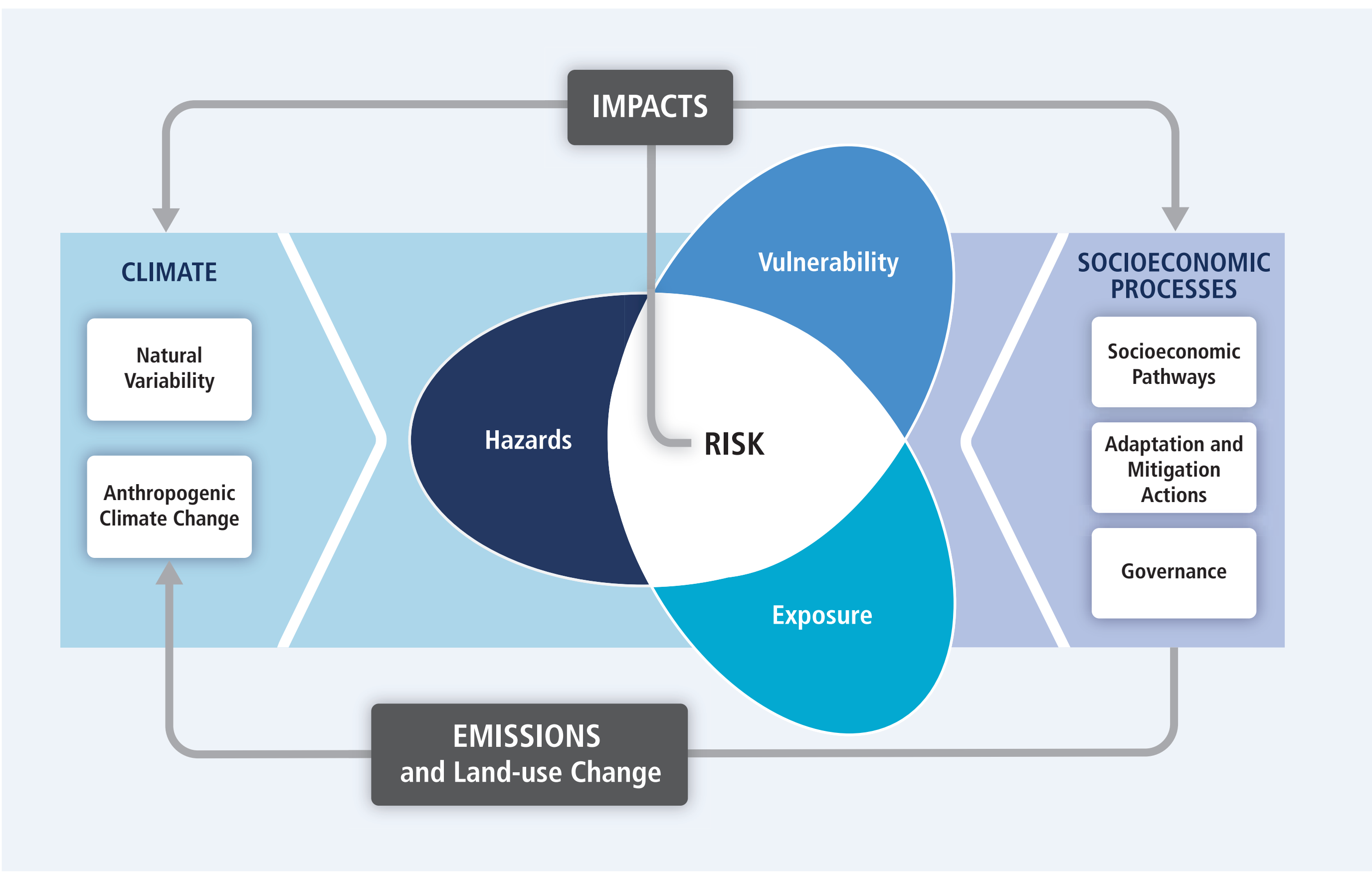

Figure TS.1 | Illustration of the core concepts of the WGII AR5. Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. Changes in both the climate system (left) and socioeconomic processes including adaptation and mitigation (right) are drivers of hazards, exposure, and vulnerability. [19.2, Figure 19-1]

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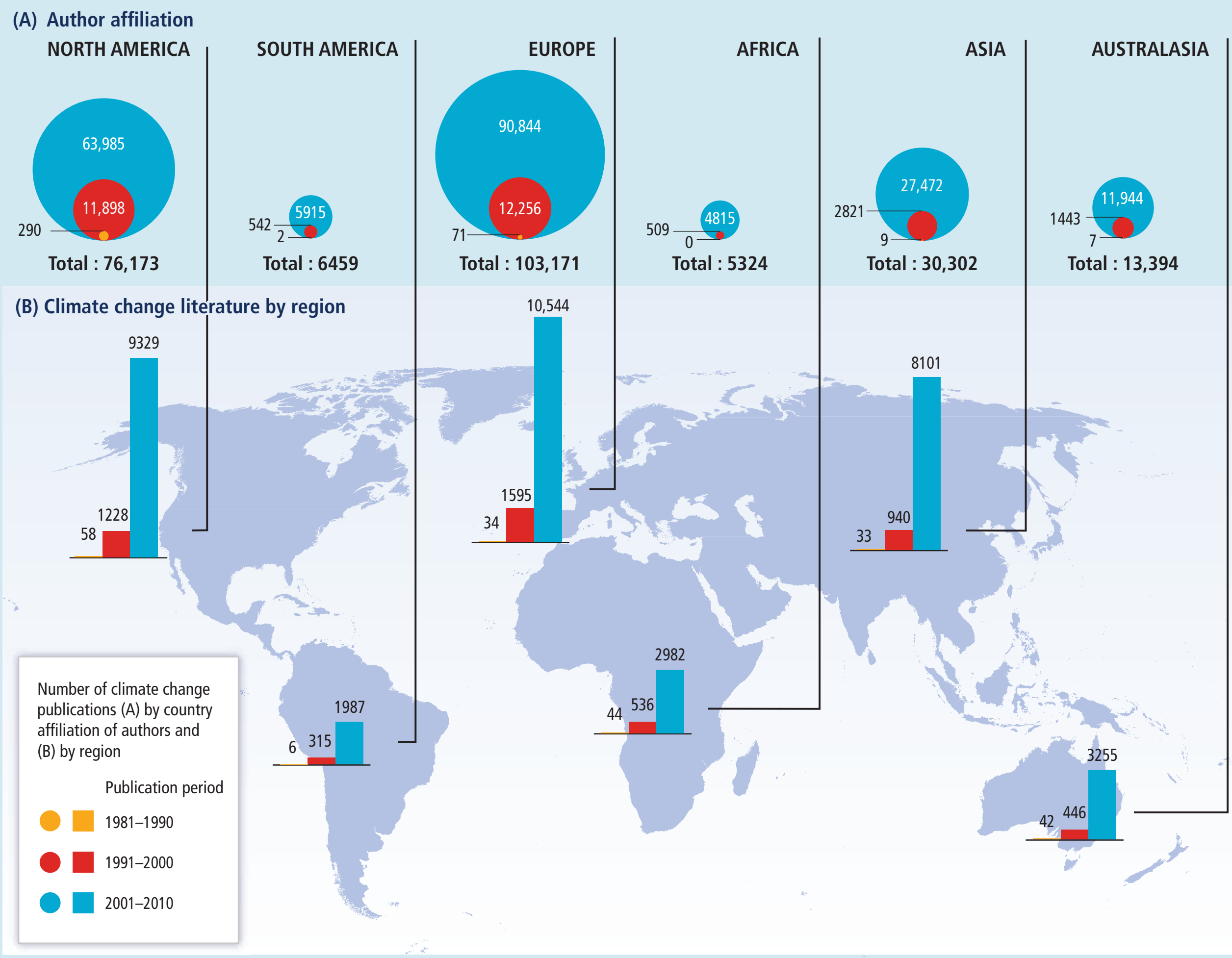
Box TS.1 | Context for the Assessment

For the past 2 decades, IPCC's Working Group II has developed assessments of climate change impacts, adaptation, and vulnerability. The WGII AR5 builds from the WGII contribution to the IPCC's Fourth Assessment Report (WGII AR4), published in 2007, and the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX), published in 2012. It follows the Working Group I contribution to the AR5 (WGI AR5). The WGII AR5 is presented in two parts (Part A: Global and Sectoral Aspects, and Part B: Regional Aspects), reflecting the expanded literature basis and multidisciplinary approach, increased focus on societal impacts and responses, and continued regionally comprehensive coverage. [1.1 to 1.3]

The number of scientific publications available for assessing climate change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, with especially rapid increases in publications related to adaptation, allowing for a more robust assessment that supports policymaking (*high confidence*). The diversity of the topics and regions covered has similarly expanded, as has the geographic distribution of authors contributing to the knowledge base for climate change assessments (Box TS.1 Figure 1). Authorship of climate change publications from developing countries has increased, although it still represents a small fraction of the total. The unequal distribution of publications presents a challenge to the production of a comprehensive and balanced global assessment. [1.1, Figure 1-1]



Box TS.1 Figure 1 | Number of climate change publications listed in the Scopus bibliographic database. (A) Number of climate change publications in English (as of July 2011) summed by country affiliation of all authors of the publications and sorted by region. Each publication can be counted multiple times (i.e., the number of different countries in the author affiliation list). (B) Number of climate change publications in English with individual countries mentioned in title, abstract, or key words (as of July 2011) sorted by region for the decades 1981–1990, 1991–2000, and 2001–2010. Each publication can be counted multiple times if more than one country is listed. [Figure 1-1]

Continued next page →

Box TS.1 (continued)

Adaptation has emerged as a central area in climate change research, in country-level planning, and in implementation of climate change strategies (*high confidence*). The body of literature, including government and private sector reports, shows an increased focus on adaptation opportunities and the interrelations between adaptation, mitigation, and alternative sustainable pathways. The literature shows an emergence of studies on transformative processes that take advantage of synergies between adaptation planning, development strategies, social protection, and disaster risk reduction and management. [1.1]

As a core feature and innovation of IPCC assessment, major findings are presented with defined, calibrated language that communicates the strength of scientific understanding, including uncertainties and areas of disagreement (Box TS.3). Each finding is supported by a traceable account of the evaluation of evidence and agreement. [1.1, Box 1-1]

Box TS.2 | Terms Central for Understanding the Summary

Central concepts defined in the WGII AR5 glossary and used throughout the report include the following terms. Reflecting progress in science, some definitions differ in breadth and focus from the definitions used in the AR4 and other IPCC reports.

Climate change: Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes.

Hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term *hazard* usually refers to climate-related physical events or trends or their physical impacts.

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Impacts: Effects on natural and human systems. In this report, the term *impacts* is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as *consequences* and *outcomes*. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.

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Box TS.2 (continued)

Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard (see Figure TS.1). In this report, the term *risk* is used primarily to refer to the risks of climate-change impacts.

Adaptation: The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

Incremental adaptation: Adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale.

Transformational adaptation: Adaptation that changes the fundamental attributes of a system in response to climate and its effects.

Transformation: A change in the fundamental attributes of natural and human systems.

Resilience: The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.

exposure, evaluating the sensitivity of systems to climate change. The section also identifies challenges and options based on adaptation experience, looking at what has motivated previous adaptation actions in the context of climate change and broader objectives. It examines current understanding of decision making as relevant to climate change.

A-1. Observed Impacts, Vulnerability, and Exposure

In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. This conclusion is strengthened by more numerous and improved observations and analyses since the AR4. Evidence of climate-change impacts is strongest and most comprehensive for natural systems. Some impacts on human systems have also been attributed to climate change, with a major or minor contribution of climate change distinguishable from other influences such as changing social and economic factors. In many regions, impacts on natural and human systems are now detected even in the presence of strong confounding factors such as pollution or land use change. See Figure TS.2 and Table TS.1 for a summary of observed impacts, illustrating broader trends presented in this section. Attribution of observed impacts in the WGII AR5 generally links responses of natural and human systems to observed climate change, regardless of its cause. Most reported impacts of climate change are attributed to warming and/or to shifts in precipitation patterns. There is also emerging evidence of impacts of ocean acidification. Relatively few robust attribution studies and meta-analyses have linked impacts in physical and biological systems to anthropogenic climate change. [18.1, 18.3 to 18.6]

Differences in vulnerability and exposure arise from non-climatic factors and from multidimensional inequalities often produced by uneven development processes (*very high confidence*). These differences shape differential risks from climate change. See Figure TS.1 and Box TS.4. Vulnerability and exposure vary over time and across geographic contexts. Changes in poverty or socioeconomic status, ethnic composition, age structure, and governance have had a significant influence on the outcome of past crises associated with climate-related hazards. [8.2, 9.3, 12.2, 13.1, 13.2, 14.1 to 14.3, 19.2, 19.6, 26.8, Box CC-GC]

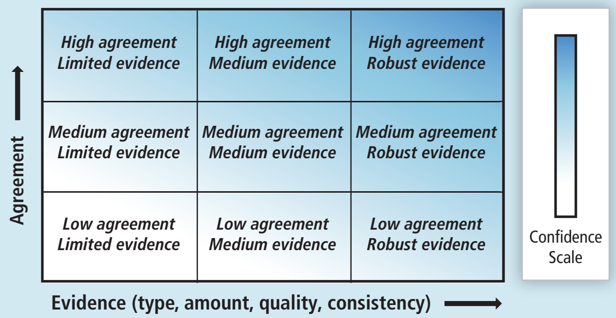
Impacts from recent climate-related extremes, such as heat waves, droughts, floods, cyclones, and wildfires, reveal significant vulnerability and exposure of some ecosystems and many human systems to current climate variability (*very high confidence*). Impacts of such climate-related extremes include alteration of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, morbidity and mortality, and consequences for mental health and human well-being. For countries at all levels of development, these impacts are consistent with a significant lack of preparedness for current climate variability in some sectors. The following examples

Box TS.3 | Communication of the Degree of Certainty in Assessment Findings

Based on the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, the WGII AR5 relies on two metrics for communicating the degree of certainty in key findings:

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively.
- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations or model results, or both, and expert judgment).

Each finding has its foundation in evaluation of associated evidence and agreement. The summary terms to describe evidence are: *limited*, *medium*, or *robust*; and agreement: *low*, *medium*, or *high*. These terms are presented with some key findings. In many cases, assessment authors in addition evaluate their confidence about the validity of a finding, providing a synthesis of the evaluation of evidence and agreement. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*. Box TS.3 Figure 1 illustrates the flexible relationship between the summary terms for evidence and agreement and the confidence metric. For a given evidence and agreement statement, different confidence levels could be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.



Box TS.3 Figure 1 | Evidence and agreement statements and their relationship to confidence. The shading increasing toward the top right corner indicates increasing confidence. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence. [Figure 1-3]

When assessment authors evaluate the likelihood, or probability, of some well-defined outcome having occurred or occurring in the future, a finding can include likelihood terms (see below) or a more precise presentation of probability. Use of likelihood is not an alternative to use of confidence. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high* confidence.

Term	Likelihood of the outcome
Virtually certain	99–100% probability
Extremely likely	95–100% probability
Very likely	90–100% probability
Likely	66–100% probability
More likely than not	>50–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Extremely unlikely	0–5% probability
Exceptionally unlikely	0–1% probability

Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers.

Within paragraphs of this summary, the confidence, evidence, and agreement terms given for a key finding apply to subsequent statements in the paragraph, unless additional terms are provided.

[1.1, Box 1-1]

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illustrate impacts of extreme weather and climate events experienced across regional contexts:

- In Africa, extreme weather and climate events including droughts and floods have significant impacts on economic sectors, natural resources, ecosystems, livelihoods, and human health. The floods of the Zambezi River in Mozambique in 2008, for example, displaced 90,000 people, and along the Zambezi River Valley, with approximately 1 million people living in the flood-affected areas, temporary displacement is taking on permanent characteristics. [22.3, 22.4, 22.6]
- Recent floods in Australia and New Zealand caused severe damage to infrastructure and settlements and 35 deaths in Queensland alone (2011). The Victorian heat wave (2009) increased heat-related morbidity and was associated with more than 300 excess deaths, while intense bushfires destroyed more than 2000 buildings and led to 173 deaths. Widespread drought in southeast Australia (1997–2009) and many parts of New Zealand (2007–2009; 2012–2013) resulted in economic losses (e.g., regional GDP in the southern Murray-Darling Basin was below forecast by about 5.7% in 2007–2008, and New Zealand lost about NZ$3.6 billion in direct and off-farm output in 2007–2009). [13.2, 25.6, 25.8, Table 25-1, Boxes 25-5, 25-6, and 25-8]
- In Europe, extreme weather events currently have significant impacts in multiple economic sectors as well as adverse social and health effects (*high confidence*). [Table 23-1]
- In North America, most economic sectors and human systems have been affected by and have responded to extreme weather, including hurricanes, flooding, and intense rainfall (*high confidence*). Extreme heat events currently result in increases in mortality and morbidity (*very high confidence*), with impacts that vary by age, location, and socioeconomic factors (*high confidence*). Extreme coastal storm events have caused excess mortality and morbidity, particularly along the east coast of the United States, and the gulf coast of both Mexico and the United States. Much North American infrastructure is currently vulnerable to extreme weather events (*medium confidence*), with deteriorating water-resource and transportation infrastructure particularly vulnerable (*high confidence*). [26.6, 26.7, Figure 26-2]
- In the Arctic, extreme weather events have had direct and indirect adverse health effects for residents (*high confidence*). [28.2]

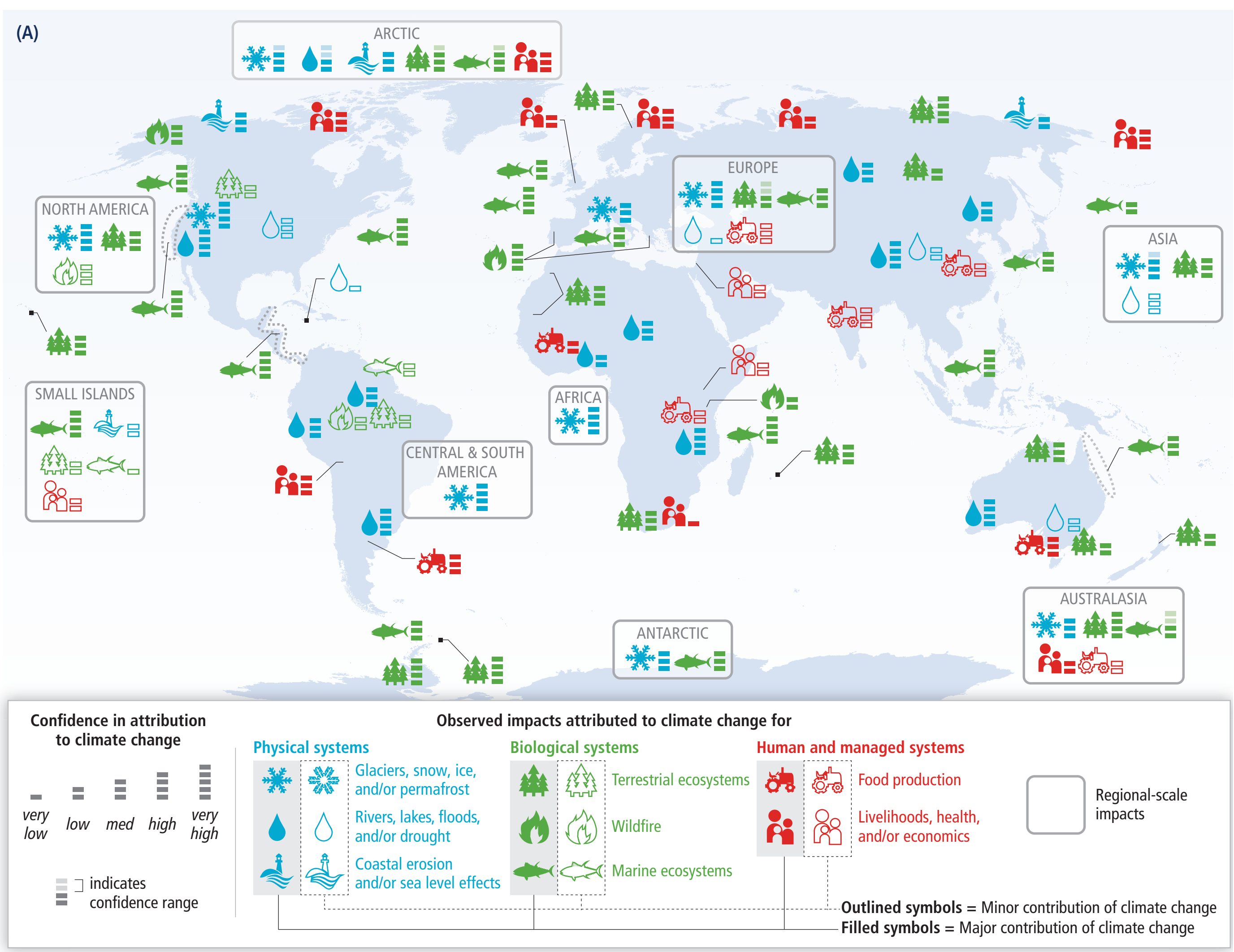

Figure TS.2

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Figure TS.2 (continued)

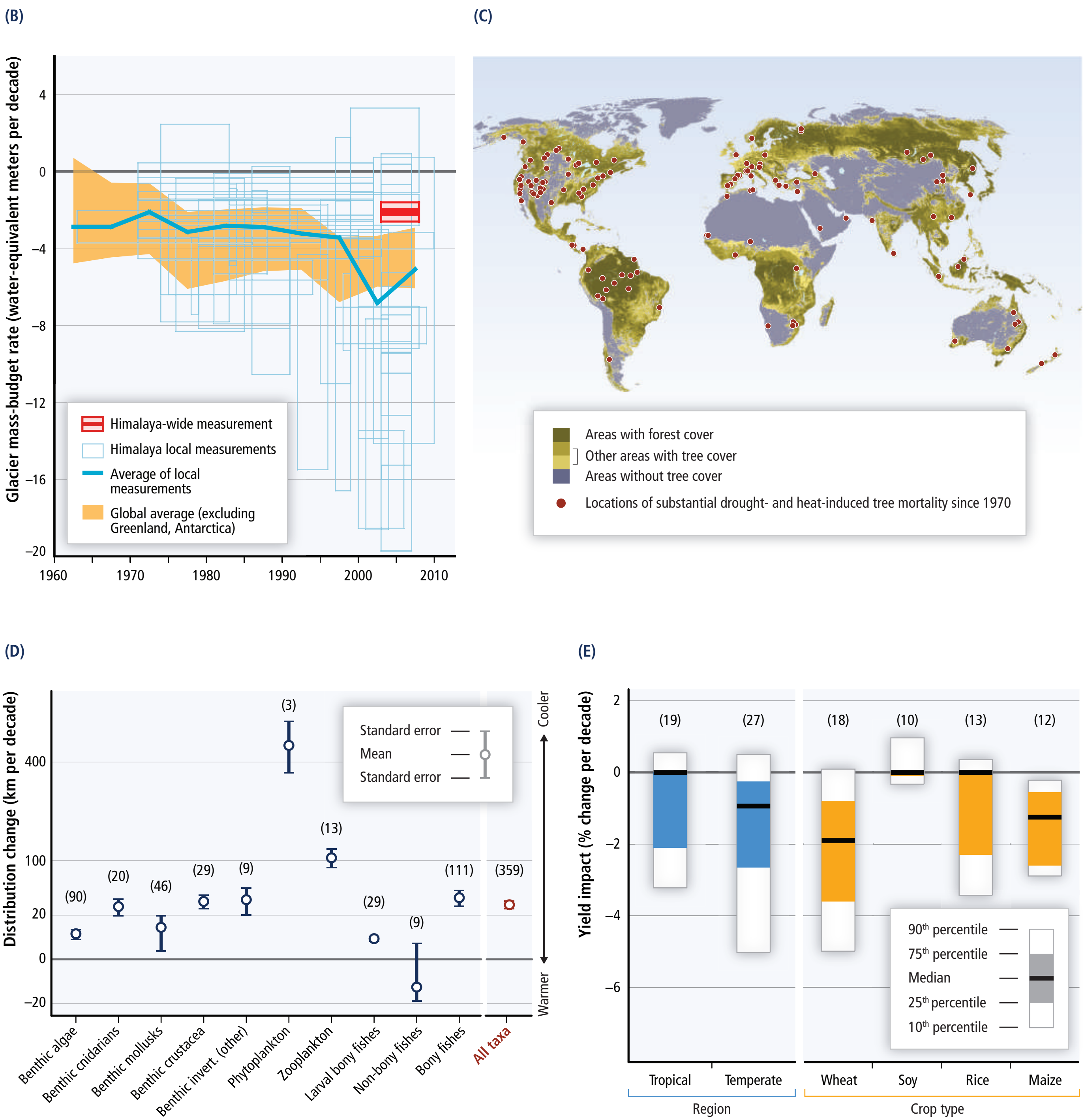

Figure TS.2 | Widespread impacts in a changing world. (A) Global patterns of impacts in recent decades attributed to climate change, based on studies since the AR4. Impacts are shown at a range of geographic scales. Symbols indicate categories of attributed impacts, the relative contribution of climate change (major or minor) to the observed impact, and confidence in attribution. See Table TS.1 for descriptions of the impacts. (B) Changes in glacier mass from all published measurements for Himalayan glaciers. Negative values indicate loss of glacier mass. Local measurements are mostly for small, accessible Himalayan glaciers. The blue box for each local Himalaya measurement is centered vertically on its average, and has a height of ±1 standard deviation for annual measurements and a height of ±1 standard error for multiannual measurements. Himalaya-wide measurement (red) was made by satellite laser altimetry. For reference, global average glacier mass change estimates from WGI AR5 4.3 are also shown, with shading indicating ±1 standard deviation. (C) Locations of substantial drought- and heat-induced tree mortality around the globe over 1970–2011. (D) Average rates of change in distribution (km per decade) for marine taxonomic groups based on observations over 1900–2010. Positive distribution changes are consistent with warming (moving into previously cooler waters, generally poleward). The number of responses analyzed is given within parentheses for each category. (E) Summary of estimated impacts of observed climate changes on yields over 1960–2013 for four major crops in temperate and tropical regions, with the number of data points analyzed given within parentheses for each category. [Figures 3-3, 4-7, 7-2, 18-3, and MB-2]

Freshwater Resources

In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources in terms of quantity and quality (*medium confidence*). Glaciers continue to shrink almost worldwide due to climate change (*high confidence*) (e.g., Figure TS.2B), affecting runoff and water resources downstream (*medium confidence*). Climate change is causing permafrost warming and thawing in high-latitude regions and in high-elevation regions (*high confidence*). There is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand. [3.2, 4.3, 18.3, 18.5, 24.4, 25.5, 26.2, 28.2, Tables 3-1 and 25-1, Figures 18-2 and 26-1]

Terrestrial and Freshwater Ecosystems

Many terrestrial and freshwater plant and animal species have shifted their geographic ranges and seasonal activities and altered their abundance in response to observed climate change over recent decades, and they are doing so now in many regions (*high confidence*). Increased tree mortality, observed in many places worldwide, has been attributed to climate change in some regions (Figure TS.2C). Increases in the frequency or intensity of ecosystem disturbances such as droughts, wind storms, fires, and pest outbreaks have been detected in many parts of the world and in some cases are attributed to climate change (*medium confidence*). While recent climate change contributed to the extinction of some species of Central American amphibians (*medium confidence*), most recent observed terrestrial

Table TS.1 | Observed impacts attributed to climate change reported in the scientific literature since the AR4. These impacts have been attributed to climate change with *very low*, *low*, *medium*, or *high confidence*, with the relative contribution of climate change to the observed change indicated (major or minor), for natural and human systems across eight major world regions over the past several decades. [Tables 18-5 to 18-9] Absence from the table of additional impacts attributed to climate change does not imply that such impacts have not occurred.

	Africa
Snow & Ice, Rivers & Lakes, Floods & Drought	• Retreat of tropical highland glaciers in East Africa (*high confidence*, major contribution from climate change) • Reduced discharge in West African rivers (*low confidence*, major contribution from climate change) • Lake surface warming and water column stratification increases in the Great Lakes and Lake Kariba (*high confidence*, major contribution from climate change) • Increased soil moisture drought in the Sahel since 1970, partially wetter conditions since 1990 (*medium confidence*, major contribution from climate change) [22.2, 22.3, Tables 18-5, 18-6, and 22-3]
Terrestrial Ecosystems	• Tree density decreases in western Sahel and semi-arid Morocco, beyond changes due to land use (*medium confidence*, major contribution from climate change) • Range shifts of several southern plants and animals, beyond changes due to land use (*medium confidence*, major contribution from climate change) • Increases in wildfires on Mt. Kilimanjaro (*low confidence*, major contribution from climate change) [22.3, Tables 18-7 and 22-3]
Coastal Erosion & Marine Ecosystems	• Decline in coral reefs in tropical African waters, beyond decline due to human impacts (*high confidence*, major contribution from climate change) [Table 18-8]
Food Production & Livelihoods	• Adaptive responses to changing rainfall by South African farmers, beyond changes due to economic conditions (*very low confidence*, major contribution from climate change) • Decline in fruit-bearing trees in Sahel (*low confidence*, major contribution from climate change) • Malaria increases in Kenyan highlands, beyond changes due to vaccination, drug resistance, demography, and livelihoods (*low confidence*, minor contribution from climate change) • Reduced fisheries productivity of Great Lakes and Lake Kariba, beyond changes due to fisheries management and land use (*low confidence*, minor contribution from climate change) [7.2, 11.5, 13.2, 22.3, Table 18-9]
	Europe
Snow & Ice, Rivers & Lakes, Floods & Drought	• Retreat of Alpine, Scandinavian, and Icelandic glaciers (*high confidence*, major contribution from climate change) • Increase in rock slope failures in western Alps (*medium confidence*, major contribution from climate change) • Changed occurrence of extreme river discharges and floods (*very low confidence*, minor contribution from climate change) [18.3, 23.2, 23.3, Tables 18-5 and 18-6; WGI AR5 4.3]
Terrestrial Ecosystems	• Earlier greening, leaf emergence, and fruiting in temperate and boreal trees (*high confidence*, major contribution from climate change) • Increased colonization of alien plant species in Europe, beyond a baseline of some invasion (*medium confidence*, major contribution from climate change) • Earlier arrival of migratory birds in Europe since 1970 (*medium confidence*, major contribution from climate change) • Upward shift in tree-line in Europe, beyond changes due to land use (*low confidence*, major contribution from climate change) • Increasing burnt forest areas during recent decades in Portugal and Greece, beyond some increase due to land use (*high confidence*, major contribution from climate change) [4.3, 18.3, Tables 18-7 and 23-6]
Coastal Erosion & Marine Ecosystems	• Northward distributional shifts of zooplankton, fishes, seabirds, and benthic invertebrates in northeast Atlantic (*high confidence*, major contribution from climate change) • Northward and depth shift in distribution of many fish species across European seas (*medium confidence*, major contribution from climate change) • Plankton phenology changes in northeast Atlantic (*medium confidence*, major contribution from climate change) • Spread of warm water species into the Mediterranean, beyond changes due to invasive species and human impacts (*medium confidence*, major contribution from climate change) [6.3, 23.6, 30.5, Tables 6-2 and 18-8, Boxes 6-1 and CC-MB]
Food Production & Livelihoods	• Shift from cold-related mortality to heat-related mortality in England and Wales, beyond changes due to exposure and health care (*low confidence*, major contribution from climate change) • Impacts on livelihoods of Sámi people in northern Europe, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) • Stagnation of wheat yields in some countries in recent decades, despite improved technology (*medium confidence*, minor contribution from climate change) • Positive yield impacts for some crops mainly in northern Europe, beyond increase due to improved technology (*medium confidence*, minor contribution from climate change) • Spread of bluetongue virus in sheep and of ticks across parts of Europe (*medium confidence*, minor contribution from climate change) [18.4, 23.4, 23.5, Table 18-9, Figure 7-2]

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Table TS.1 (continued)

Asia	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Permafrost degradation in Siberia, Central Asia, and Tibetan Plateau (*high confidence*, major contribution from climate change) • Shrinking mountain glaciers across most of Asia (*medium confidence*, major contribution from climate change) • Changed water availability in many Chinese rivers, beyond changes due to land use (*low confidence*, minor contribution from climate change) • Increased flow in several rivers due to shrinking glaciers (*high confidence*, major contribution from climate change) • Earlier timing of maximum spring flood in Russian rivers (*medium confidence*, major contribution from climate change) • Reduced soil moisture in north-central and northeast China (1950–2006) (*medium confidence*, major contribution from climate change) • Surface water degradation in parts of Asia, beyond changes due to land use (*medium confidence*, minor contribution from climate change) [24.3, 24.4, 28.2, Tables 18-5, 18-6, and SM24-4, Box 3-1; WGI AR5 4.3, 10.5]
Terrestrial Ecosystems	• Changes in plant phenology and growth in many parts of Asia (earlier greening), particularly in the north and east (*medium confidence*, major contribution from climate change) • Distribution shifts of many plant and animal species upwards in elevation or polewards, particularly in the north of Asia (*medium confidence*, major contribution from climate change) • Invasion of Siberian larch forests by pine and spruce during recent decades (*low confidence*, major contribution from climate change) • Advance of shrubs into the Siberian tundra (*high confidence*, major contribution from climate change) [4.3, 24.4, 28.2, Table 18-7, Figure 4-4]
Coastal Erosion & Marine Ecosystems	• Decline in coral reefs in tropical Asian waters, beyond decline due to human impacts (*high confidence*, major contribution from climate change) • Northward range extension of corals in the East China Sea and western Pacific, and of a predatory fish in the Sea of Japan (*medium confidence*, major contribution from climate change) • Shift from sardines to anchovies in the western North Pacific, beyond fluctuations due to fisheries (*low confidence*, major contribution from climate change) • Increased coastal erosion in Arctic Asia (*low confidence*, major contribution from climate change) [6.3, 24.4, 30.5, Tables 6-2 and 18-8]
Food Production & Livelihoods	• Impacts on livelihoods of indigenous groups in Arctic Russia, beyond economic and sociopolitical changes (*low confidence*, major contribution from climate change) • Negative impacts on aggregate wheat yields in South Asia, beyond increase due to improved technology (*medium confidence*, minor contribution from climate change) • Negative impacts on aggregate wheat and maize yields in China, beyond increase due to improved technology (*low confidence*, minor contribution from climate change) • Increases in a water-borne disease in Israel (*low confidence*, minor contribution from climate change) [7.2, 13.2, 18.4, 28.2, Tables 18-4 and 18-9, Figure 7-2]
Australasia	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Significant decline in late-season snow depth at 3 of 4 alpine sites in Australia (1957–2002) (*medium confidence*, major contribution from climate change) • Substantial reduction in ice and glacier ice volume in New Zealand (*medium confidence*, major contribution from climate change) • Intensification of hydrological drought due to regional warming in southeast Australia (*low confidence*, minor contribution from climate change) • Reduced inflow in river systems in southwestern Australia (since the mid-1970s) (*high confidence*, major contribution from climate change) [25.5, Tables 18-5, 18-6, and 25-1; WGI AR5 4.3]
Terrestrial Ecosystems	• Changes in genetics, growth, distribution, and phenology of many species, in particular birds, butterflies, and plants in Australia, beyond fluctuations due to variable local climates, land use, pollution, and invasive species (*high confidence*, major contribution from climate change) • Expansion of some wetlands and contraction of adjacent woodlands in southeast Australia (*low confidence*, major contribution from climate change) • Expansion of monsoon rainforest at expense of savannah and grasslands in northern Australia (*medium confidence*, major contribution from climate change) • Migration of glass eels advanced by several weeks in Waikato River, New Zealand (*low confidence*, major contribution from climate change) [Tables 18-7 and 25-3]
Coastal Erosion & Marine Ecosystems	• Southward shifts in the distribution of marine species near Australia, beyond changes due to short-term environmental fluctuations, fishing, and pollution (*medium confidence*, major contribution from climate change) • Change in timing of migration of seabirds in Australia (*low confidence*, major contribution from climate change) • Increased coral bleaching in Great Barrier Reef and western Australian reefs, beyond effects from pollution and physical disturbance (*high confidence*, major contribution from climate change) • Changed coral disease patterns at Great Barrier Reef, beyond effects from pollution (*medium confidence*, major contribution from climate change) [6.3, 25.6, Tables 18-8 and 25-3]
Food Production & Livelihoods	• Advanced timing of wine-grape maturation in recent decades, beyond advance due to improved management (*medium confidence*, major contribution from climate change) • Shift in winter vs. summer human mortality in Australia, beyond changes due to exposure and health care (*low confidence*, major contribution from climate change) • Relocation or diversification of agricultural activities in Australia, beyond changes due to policy, markets, and short-term climate variability (*low confidence*, minor contribution from climate change) [11.4, 18.4, 25.7, 25.8, Tables 18-9 and 25-3, Box 25-5]
North America	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Shrinkage of glaciers across western and northern North America (*high confidence*, major contribution from climate change) • Decreasing amount of water in spring snowpack in western North America (1960–2002) (*high confidence*, major contribution from climate change) • Shift to earlier peak flow in snow dominated rivers in western North America (*high confidence*, major contribution from climate change) • Increased runoff in the midwestern and northeastern US (*medium confidence*, minor contribution from climate change) [Tables 18-5 and 18-6; WGI AR5 2.6, 4.3]
Terrestrial Ecosystems	• Phenology changes and species distribution shifts upward in elevation and northward across multiple taxa (*medium confidence*, major contribution from climate change) • Increased wildfire frequency in subarctic conifer forests and tundra (*medium confidence*, major contribution from climate change) • Regional increases in tree mortality and insect infestations in forests (*low confidence*, minor contribution from climate change) • Increase in wildfire activity, fire frequency and duration, and burnt area in forests of the western US and boreal forests in Canada, beyond changes due to land use and fire management (*medium confidence*, minor contribution from climate change) [26.4, 28.2, Table 18-7, Box 26-2]
Coastal Erosion & Marine Ecosystems	• Northward distributional shifts of northwest Atlantic fish species (*high confidence*, major contribution from climate change) • Changes in musselbeds along the west coast of US (*high confidence*, major contribution from climate change) • Changed migration and survival of salmon in northeast Pacific (*high confidence*, major contribution from climate change) • Increased coastal erosion in Alaska and Canada (*medium confidence*, major contribution from climate change) [18.3, 30.5, Tables 6-2 and 18-8]
Food Production & Livelihoods	• Impacts on livelihoods of indigenous groups in the Canadian Arctic, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) [18.4, 28.2, Tables 18-4 and 18-9]

Continued next page →

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Table TS.1 (continued)

Central and South America	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Shrinkage of Andean glaciers (*high confidence*, major contribution from climate change) • Changes in extreme flows in Amazon River (*medium confidence*, major contribution from climate change) • Changing discharge patterns in rivers in the western Andes (*medium confidence*, major contribution from climate change) • Increased streamflow in sub-basins of the La Plata River, beyond increase due to land-use change (*high confidence*, major contribution from climate change) [27.3, Tables 18-5, 18-6, and 27-3; WGI AR5 4.3]
Terrestrial Ecosystems	• Increased tree mortality and forest fire in the Amazon (*low confidence*, minor contribution from climate change) • Rainforest degradation and recession in the Amazon, beyond reference trends in deforestation and land degradation (*low confidence*, minor contribution from climate change) [4.3, 18.3, 27.2, 27.3, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coral bleaching in western Caribbean, beyond effects from pollution and physical disturbance (*high confidence*, major contribution from climate change) • Mangrove degradation on north coast of South America, beyond degradation due to pollution and land use (*low confidence*, minor contribution from climate change) [27.3, Table 18-8]
Food Production & Livelihoods	• More vulnerable livelihood trajectories for indigenous Aymara farmers in Bolivia due to water shortage, beyond effects of increasing social and economic stress (*medium confidence*, major contribution from climate change) • Increase in agricultural yields and expansion of agricultural areas in southeastern South America, beyond increase due to improved technology (*medium confidence*, major contribution from climate change) [13.1, 27.3, Table 18-9]
Polar Regions	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Decreasing Arctic sea ice cover in summer (*high confidence*, major contribution from climate change) • Reduction in ice volume in Arctic glaciers (*high confidence*, major contribution from climate change) • Decreasing snow cover extent across the Arctic (*medium confidence*, major contribution from climate change) • Widespread permafrost degradation, especially in the southern Arctic (*high confidence*, major contribution from climate change) • Ice mass loss along coastal Antarctica (*medium confidence*, major contribution from climate change) • Increased river discharge for large circumpolar rivers (1997–2007) (*low confidence*, major contribution from climate change) • Increased winter minimum river flow in most of the Arctic (*medium confidence*, major contribution from climate change) • Increased lake water temperatures 1985–2009 and prolonged ice-free seasons (*medium confidence*, major contribution from climate change) • Disappearance of thermokarst lakes due to permafrost degradation in the low Arctic. New lakes created in areas of formerly frozen peat (*high confidence*, major contribution from climate change) [28.2, Tables 18-5 and 18-6; WGI AR5 4.2 to 4.4, 4.6, 10.5]
Terrestrial Ecosystems	• Increased shrub cover in tundra in North America and Eurasia (*high confidence*, major contribution from climate change) • Advance of Arctic tree-line in latitude and altitude (*medium confidence*, major contribution from climate change) • Changed breeding area and population size of subarctic birds, due to snowbed reduction and/or tundra shrub encroachment (*medium confidence*, major contribution from climate change) • Loss of snow-bed ecosystems and tussock tundra (*high confidence*, major contribution from climate change) • Impacts on tundra animals from increased ice layers in snow pack, following rain-on-snow events (*medium confidence*, major contribution from climate change) • Increased plant species ranges in the West Antarctic Peninsula and nearby islands over the past 50 years (*high confidence*, major contribution from climate change) • Increased phytoplankton productivity in Signy Island lake waters (*high confidence*, major contribution from climate change) [28.2, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coastal erosion across Arctic (*medium confidence*, major contribution from climate change) • Negative effects on non-migratory Arctic species (*high confidence*, major contribution from climate change) • Decreased reproductive success in Arctic seabirds (*medium confidence*, major contribution from climate change) • Decline in Southern Ocean seals and seabirds (*medium confidence*, major contribution from climate change) • Reduced thickness of foraminiferal shells in southern oceans, due to ocean acidification (*medium confidence*, major contribution from climate change) • Reduced krill density in Scotia Sea (*medium confidence*, major contribution from climate change) [6.3, 18.3, 28.2, 28.3, Table 18-8]
Food Production & Livelihoods	• Impact on livelihoods of Arctic indigenous peoples, beyond effects of economic and sociopolitical changes (*medium confidence*, major contribution from climate change) • Increased shipping traffic across the Bering Strait (*medium confidence*, major contribution from climate change) [18.4, 28.2, Tables 18-4 and 18-9, Figure 28-4]
Small Islands	
Snow & Ice, Rivers & Lakes, Floods & Drought	• Increased water scarcity in Jamaica, beyond increase due to water use (*very low confidence*, minor contribution from climate change) [Table 18-6]
Terrestrial Ecosystems	• Tropical bird population changes in Mauritius (*medium confidence*, major contribution from climate change) • Decline of an endemic plant in Hawai'i (*medium confidence*, major contribution from climate change) • Upward trend in tree-lines and associated fauna on high-elevation islands (*low confidence*, minor contribution from climate change) [29.3, Table 18-7]
Coastal Erosion & Marine Ecosystems	• Increased coral bleaching near many tropical small islands, beyond effects of degradation due to fishing and pollution (*high confidence*, major contribution from climate change) • Degradation of mangroves, wetlands, and seagrass around small islands, beyond degradation due to other disturbances (*very low confidence*, minor contribution from climate change) • Increased flooding and erosion, beyond erosion due to human activities, natural erosion, and accretion (*low confidence*, minor contribution from climate change) • Degradation of groundwater and freshwater ecosystems due to saline intrusion, beyond degradation due to pollution and groundwater pumping (*low confidence*, minor contribution from climate change) [29.3, Table 18-8]
Food Production & Livelihoods	• Increased degradation of coastal fisheries due to direct effects and effects of increased coral reef bleaching, beyond degradation due to overfishing and pollution (*low confidence*, minor contribution from climate change) [18.3, 18.4, 29.3, 30.6, Table 18-9, Box CC-CR]

species extinctions have not been attributed to climate change (*high confidence*). [4.2, 4.4, 18.3, 18.5, 22.3, 25.6, 26.4, 28.2, Figure 4-10, Boxes 4-2, 4-3, 4-4, and 25-3]

Coastal Systems and Low-lying Areas

Coastal systems are particularly sensitive to changes in sea level and ocean temperature and to ocean acidification (*very high confidence*). Coral bleaching and species range shifts have been attributed to changes in ocean temperature. For many other coastal changes, the impacts of climate change are difficult to identify given other human-related drivers (e.g. land use change, coastal development, pollution) (*robust evidence*, *high agreement*). [5.3 to 5.5, 18.3, 25.6, 26.4, Box 25-3]

Marine Systems

Warming has caused and will continue to cause shifts in the abundance, geographic distribution, migration patterns, and timing of seasonal activities of marine species (*very high confidence*), paralleled by reduction in maximum body sizes (*medium confidence*). This has resulted and will further result in changing interactions between species, including competition and predator-prey dynamics (*high confidence*). Numerous observations over the last decades in all ocean basins show global-scale changes including large-scale distribution shifts of species (*very high confidence*) and altered ecosystem composition (*high confidence*) on multi-decadal time scales, tracking climate trends. Many fishes, invertebrates, and phytoplankton have shifted their distribution and/or abundance poleward and/or to deeper, cooler waters (Figure TS.2D). Some warm-water corals and their reefs have responded to warming with species replacement, bleaching, and decreased coral cover causing habitat loss. Few field observations to date demonstrate biological responses attributable to anthropogenic ocean acidification, as in many places these responses are not yet outside their natural variability and may be influenced by confounding local or regional factors. See also Box TS.7. Natural global climate change at rates slower than current anthropogenic climate change caused significant ecosystem shifts, including species emergences and extinctions, during the past millions of years. [5.4, 6.1, 6.3 to 6.5, 18.3, 18.5, 22.3, 25.6, 26.4, 30.4, 30.5, Boxes 25-3, CC-OA, CC-CR, and CC-MB]

Vulnerability of most marine organisms to warming is set by their physiology, which defines their limited temperature ranges and hence their thermal sensitivity (*high confidence*). See Figure TS.3. Temperature defines the geographic distribution of many species and their responses to climate change. Shifting temperature means and extremes alter habitat (e.g., sea ice and coastal habitat), and cause changes in species abundances through local extinctions and latitudinal distribution expansions or shifts of up to hundreds of kilometers per decade (*very high confidence*). Although genetic adaptation occurs (*medium confidence*), the capacity of fauna and flora to compensate for or keep up with the rate of ongoing thermal change is limited (*low confidence*). [6.3, 6.5, 30.5]

Oxygen minimum zones are progressively expanding in the tropical Pacific, Atlantic, and Indian Oceans, due to reduced ventilation and O_2 solubilities in more stratified oceans at higher temperatures (*high confidence*). In combination with human activities that increase the productivity of coastal systems, hypoxic areas ("dead zones") are increasing in number and size. Regional exacerbation of hypoxia causes shifts to hypoxia-tolerant biota and reduces habitat for commercially relevant species, with implications for fisheries. [6.1, 6.3, 30.3, 30.5, 30.6; WGI AR5 3.8]

Food Security and Food Production Systems

Based on many studies covering a wide range of regions and crops, negative impacts of climate change on crop yields have been more common than positive impacts (*high confidence*). The smaller number of studies showing positive impacts relate mainly to high-latitude regions, though it is not yet clear whether the balance of impacts has been negative or positive in these regions. Climate change has negatively affected wheat and maize yields for many regions and in the global aggregate (*medium confidence*). Effects on rice and soybean yield have been smaller in major production regions and globally, with a median change of zero across all available data, which are fewer for soy compared to the other crops. Observed impacts relate mainly to production aspects of food security rather than access or other components of food security. See Figure TS.2E. Since AR4, several periods of rapid food and cereal price increases following climate extremes in key producing regions indicate a sensitivity of current markets to climate extremes among other factors (*medium confidence*). Crop yields have a large negative sensitivity to extreme daytime temperatures around 30°C, throughout the growing season (*high confidence*). CO_2 has stimulatory effects on crop yields in most cases, and elevated tropospheric ozone has damaging effects. Interactions among CO_2 and ozone, mean temperature, extremes, water, and nitrogen are non-linear and difficult to predict (*medium confidence*). [7.2, 7.3, 18.4, 22.3, 26.5, Figures 7-2, 7-3, and 7-7, Box 25-3]

Urban Areas

Urban areas hold more than half the world's population and most of its built assets and economic activities. A high proportion of the population and economic activities at risk from climate change are in urban areas, and a high proportion of global greenhouse gas emissions are generated by urban-based activities and residents. Cities are composed of complex inter-dependent systems that can be leveraged to support climate change adaptation via effective city governments supported by cooperative multilevel governance (*medium confidence*). This can enable synergies with infrastructure investment and maintenance, land use management, livelihood creation, and ecosystem services protection. [8.1, 8.3, 8.4]

Rapid urbanization and growth of large cities in developing countries have been accompanied by expansion of highly vulnerable urban communities living in informal settlements, many of which are on land exposed to extreme weather (*medium confidence*). [8.2, 8.3]

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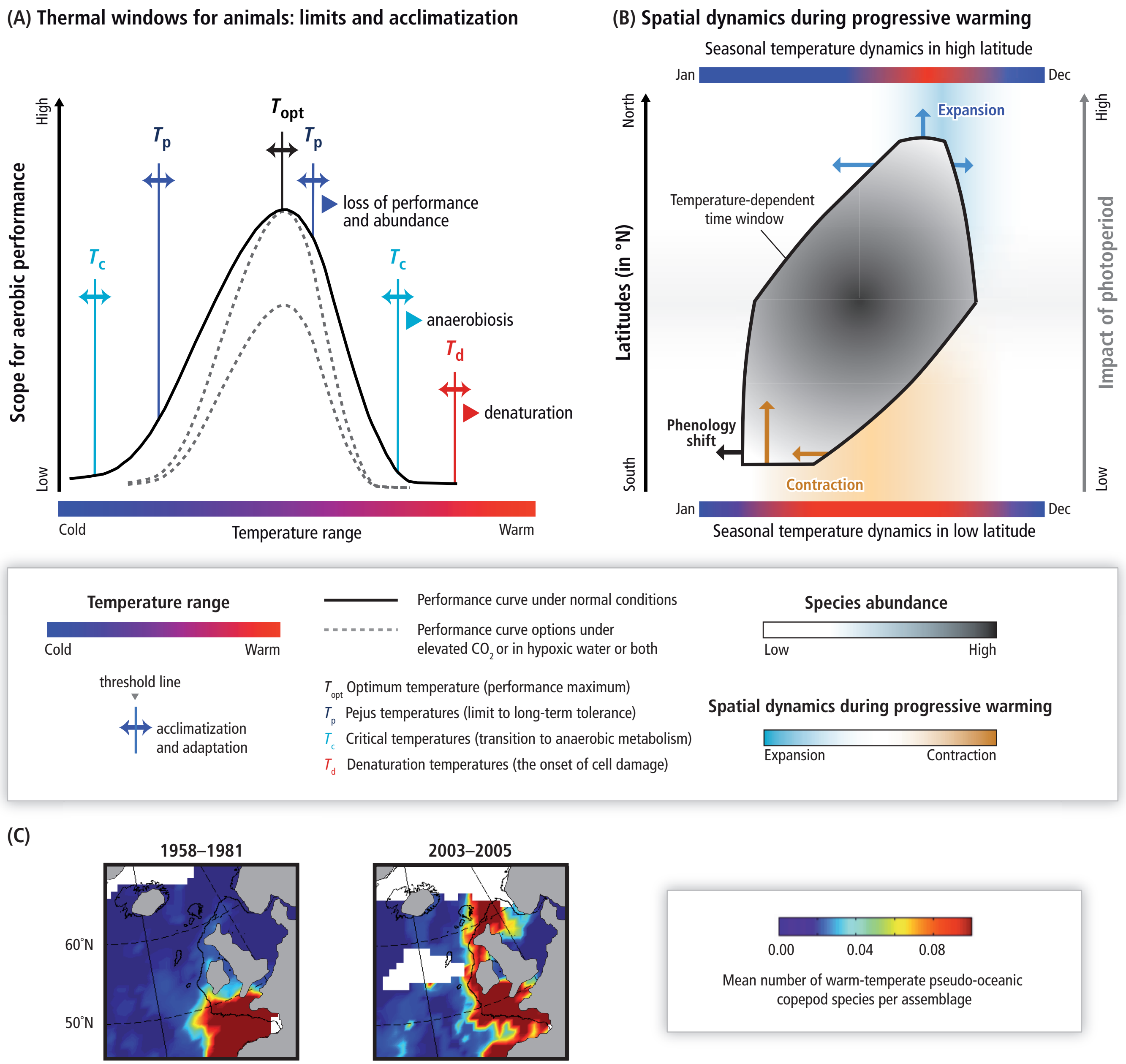


Figure TS.3 | Temperature specialization of species (A), which is influenced by other factors such as oxygen, causes warming-induced distribution shifts (B), for example, the northward expansion of warm-temperate species in the northeast Atlantic (C). These distribution changes depend on species-specific physiology and ecology. Detailed introduction of each panel follows: (A) The temperature tolerance range and performance levels of an organism are described by its performance curve. Each performance (e.g., exercise, growth, reproduction) is highest at optimum temperature (T_{opt}) and lower at cooler or warmer temperatures. Surpassing temperature thresholds (T_p) means going into time-limited tolerance, and more extreme temperature changes lead to exceedance of thresholds that cause metabolic disturbances (T_c) and ultimately onset of cell damage (T_d). These thresholds for an individual can shift (horizontal arrows), within limits, between summer and winter (seasonal acclimatization) or when the species adapts to a cooler or warmer climate over generations (evolutionary adaptation). Under elevated CO_2 levels (ocean acidification) or low oxygen, thermal windows narrow (dashed gray curves). (B) During climate warming, a species follows its normal temperatures as it moves or is displaced, typically resulting in a poleward shift of the biogeographic range (exemplified for the Northern Hemisphere). The polygon delineates the distribution range in space and seasonal time; the level of gray denotes abundance. (C) Long-term changes in the mean number of warm-temperate pseudo-oceanic copepod species in the northeast Atlantic from 1958 to 2005. [Figures 6-5, 6-7, and 6-8]

Rural Areas

Climate change in rural areas will take place in the context of many important economic, social, and land use trends (*very high confidence*). In different regions, absolute rural populations have peaked or will peak in the next few decades. The proportion of the rural population depending on agriculture is varied across regions, but declining everywhere. Poverty rates in rural areas are higher than overall poverty rates, but also falling more sharply, and the proportions of population in extreme poverty accounted for by rural people are also falling: in both cases with the exception of sub-Saharan Africa, where these rates are rising. Accelerating globalization, through migration, labor linkages, regional and international trade, and new information and communication technologies, is bringing about economic transformation in rural areas of developing and developed countries. [9.3, Figure 9-2]

For rural households and communities, access to land and natural resources, flexible local institutions, knowledge and information, and livelihood strategies can contribute to resilience to climate change (*high confidence*). Especially in developing countries, rural people are subject to multiple non-climatic stressors, including underinvestment in agriculture, problems with land and natural resource policy, and processes of environmental degradation (*very high confidence*). In developed countries, there are important shifts toward multiple uses of rural areas, especially leisure uses, and new rural policies based on the collaboration of multiple stakeholders, the targeting of multiple sectors, and a change from subsidy-based to investment-based policy. [9.3, 22.4, Table 9-3]

Key Economic Sectors and Services

Economic losses due to extreme weather events have increased globally, mostly due to increase in wealth and exposure, with a possible influence of climate change (*low confidence* in attribution to climate change). Flooding can have major economic costs, both in term of impacts (e.g., capital destruction, disruption) and adaptation (e.g., construction, defensive investment) (*robust evidence*, *high agreement*). Since the mid-20th century, socioeconomic losses from flooding have increased mainly due to greater exposure and vulnerability (*high confidence*). [3.2, 3.4, 10.3, 18.4, 23.2, 23.3, 26.7, Figure 26-2, Box 25-7]

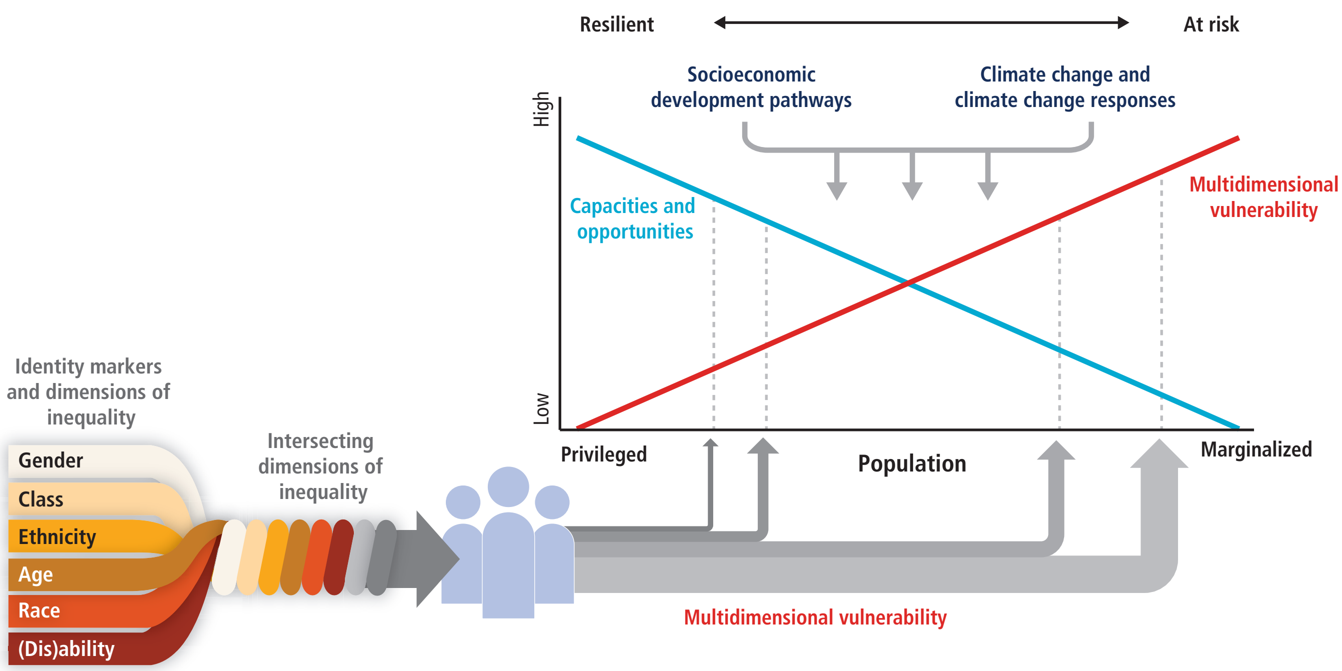
Human Health

At present the worldwide burden of human ill-health from climate change is relatively small compared with effects of other stressors and is not well quantified. However, there has been increased heat-related mortality and decreased cold-related mortality in some regions as a result of warming (*medium confidence*). Local changes in temperature and rainfall have altered the distribution of some waterborne illnesses and disease vectors (*medium confidence*). [11.4 to 11.6, 18.4, 25.8]

The health of human populations is sensitive to shifts in weather patterns and other aspects of climate change (*very high confidence*). These effects occur directly, due to changes in temperature and precipitation and in the occurrence of heat waves, floods, droughts, and fires. Health may be damaged indirectly by climate change-related ecological disruptions, such as crop failures or shifting patterns of disease vectors, or by social responses to climate change, such as displacement of populations following prolonged drought. Variability in temperatures is a risk factor in its own right, over and above the influence of average temperatures on heat-related deaths. [11.4, 28.2]

Human Security

Challenges for vulnerability reduction and adaptation actions are particularly high in regions that have shown severe difficulties in governance (*high confidence*). Violent conflict increases vulnerability to climate change (*medium evidence*, *high agreement*). Large-scale violent conflict harms assets that facilitate adaptation, including infrastructure, institutions, natural resources, social capital, and livelihood opportunities. [12.5, 19.2, 19.6]



Box TS.4 Figure 1 | Multidimensional vulnerability driven by intersecting dimensions of inequality. Vulnerability increases when people's capacities and opportunities to adapt to climate change and adjust to climate change responses are diminished. [Figure 13-5]

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Box TS.4 | Multidimensional Inequality and Vulnerability to Climate Change

People who are socially, economically, culturally, politically, institutionally, or otherwise marginalized in society are especially vulnerable to climate change and also to some adaptation and mitigation responses (*medium evidence*, *high agreement*). This heightened vulnerability is rarely due to a single cause. Rather, it is the product of intersecting social processes that result in inequalities in socioeconomic status and income, as well as in exposure. Such social processes include, for example, discrimination on the basis of gender, class, race/ethnicity, age, and (dis)ability. See Box TS.4 Figure 1 on previous page. Understanding differential capacities and opportunities of individuals, households, and communities requires knowledge of these intersecting social drivers, which may be context-specific and clustered in diverse ways (e.g., class and ethnicity in one case, gender and age in another). Few studies depict the full spectrum of these intersecting social processes and the ways in which they shape multidimensional vulnerability to climate change.

Examples of inequality-driven impacts and risks of climate change and climate change responses (*medium evidence*, *high agreement*):

- Privileged members of society can benefit from climate change impacts and response strategies, given their flexibility in mobilizing and accessing resources and positions of power, often to the detriment of others. [13.2, 13.3, 22.4, 26.8]
- Differential impacts on men and women arise from distinct roles in society, the way these roles are enhanced or constrained by other dimensions of inequality, risk perceptions, and the nature of response to hazards. [8.2, 9.3, 11.3, 12.2, 13.2, 18.4, 19.6, 22.4, Box CC-GC]
- Both male and female deaths are recorded after flooding, affected by socioeconomic disadvantage, occupation, and culturally imposed expectations to save lives. Although women are generally more sensitive to heat stress, more male workers are reported to have died largely as a result of responsibilities related to outdoor and indoor work. [11.3, 13.2, Box CC-GC]
- Women often experience additional duties as laborers and caregivers as a result of extreme weather events and climate change, as well as responses (e.g., male outmigration), while facing more psychological and emotional distress, reduced food intake, adverse mental health outcomes due to displacement, and in some cases increasing incidences of domestic violence. [9.3, 9.4, 12.4, 13.2, Box CC-GC]
- Children and the elderly are often at higher risk due to narrow mobility, susceptibility to infectious diseases, reduced caloric intake, and social isolation. While adults and older children are more severely affected by some climate-sensitive vector-borne diseases such as dengue, young children are more likely to die from or be severely compromised by diarrheal diseases and floods. The elderly face disproportional physical harm and death from heat stress, droughts, and wildfires. [8.2, 10.9, 11.1, 11.4, 11.5, 13.2, 22.4, 23.5, 26.6]
- In most urban areas, low-income groups, including migrants, face large climate change risks because of poor-quality, insecure, and clustered housing, inadequate infrastructure, and lack of provision for health care, emergency services, flood exposure, and measures for disaster risk reduction. [8.1, 8.2, 8.4, 8.5, 12.4, 22.3, 26.8]
- People disadvantaged by race or ethnicity, especially in developed countries, experience more harm from heat stress, often due to low economic status and poor health conditions, and displacement after extreme events. [11.3, 12.4, 13.2]
- Livelihoods and lifestyles of indigenous peoples, pastoralists, and fisherfolk, often dependent on natural resources, are highly sensitive to climate change and climate change policies, especially those that marginalize their knowledge, values, and activities. [9.3, 11.3, 12.3, 14.2, 22.4, 25.8, 26.8, 28.2]
- Disadvantaged groups without access to land and labor, including female-headed households, tend to benefit less from climate change response mechanisms (e.g., Clean Development Mechanism (CDM), Reduction of Emissions from Deforestation and Forest Degradation (REDD+), large-scale land acquisition for biofuels, and planned agricultural adaptation projects). [9.3, 12.2, 12.5, 13.3, 22.4, 22.6]

Livelihoods and Poverty

Climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty (*high confidence*). Climate-related hazards affect poor people's lives directly through impacts on livelihoods, reductions in crop yields, or destruction of homes and indirectly through, for example, increased food prices and food insecurity. Urban and rural transient poor who face multiple deprivations can slide into chronic poverty as a result of extreme events, or a series of events, when unable to rebuild their eroded assets (*limited evidence*, *high agreement*). Observed positive effects for poor and marginalized people, which are limited and often indirect, include examples such as diversification of social networks and of agricultural practices. [8.2, 8.3, 9.3, 11.3, 13.1 to 13.3, 22.3, 24.4, 26.8]

Livelihoods of indigenous peoples in the Arctic have been altered by climate change, through impacts on food security and traditional and cultural values (*medium confidence*). There is emerging evidence of climate change impacts on livelihoods of indigenous people in other regions. [18.4, Table 18-9, Box 18-5]

A-2. Adaptation Experience

Throughout history, people and societies have adjusted to and coped with climate, climate variability, and extremes, with varying degrees of success. This section focuses on adaptive human responses to observed and projected climate-change impacts, which can also address broader risk-reduction and development objectives.

Adaptation is becoming embedded in some planning processes, with more limited implementation of responses (*high confidence*). Engineered and technological options are commonly implemented adaptive responses, often integrated within existing programs such as disaster risk management and water management. There is increasing recognition of the value of social, institutional, and ecosystem-based measures and of the extent of constraints to adaptation. Adaptation options adopted to date continue to emphasize incremental adjustments and co-benefits and are starting to emphasize flexibility and learning (*medium evidence*, *medium agreement*). [4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 14.1, 14.3, 15.2 to 15.5, 17.2, 17.3, 22.4, 23.7, 25.4, 25.10, 26.8, 26.9, 27.3, 30.6, Boxes 25-1, 25-2, 25-9, and CC-EA]

Most assessments of adaptation have been restricted to impacts, vulnerability, and adaptation planning, with very few assessing the processes of implementation or the effects of adaptation actions (*medium evidence*, *high agreement*). Vulnerability indicators define, quantify, and weight aspects of vulnerability across regional units, but methods of constructing indices are subjective, often lack transparency, and can be difficult to interpret. There are conflicting views on the choice of adaptation metrics, given differing values placed on needs and outcomes, many of which cannot be captured in a comparable way by metrics. Indicators proving most useful for policy learning are those that track not just process and implementation, but also the extent to which targeted outcomes are occurring. Multi-metric evaluations including risk and uncertainty are increasingly used, an evolution from a previous focus on cost-benefit analysis and identification of "best economic adaptations" (*high confidence*). Adaptation assessments best suited to delivering effective adaptation measures often include both top-down assessments of biophysical climate changes and bottom-up assessments of vulnerability targeted toward local solutions to globally derived risks and toward particular decisions. [4.4, 14.4, 14.5, 15.2, 15.3, 17.2, 17.3, 21.3, 21.5, 22.4, 25.4, 25.10, 26.8, 26.9, Box CC-EA]

Adaptation experience is accumulating across regions in the public and private sector and within communities (*high confidence*). Governments at various levels are starting to develop adaptation plans and policies and to integrate climate-change considerations into broader development plans. Examples of adaptation across regions and contexts include the following:

- Urban adaptation has emphasized city-based disaster risk management such as early warning systems and infrastructure investments; ecosystem-based adaptation and green roofs; enhanced storm and wastewater management; urban and peri-urban agriculture improving food security; enhanced social protection; and good-quality, affordable, and well-located housing (*high confidence*). [8.3, 8.4, 15.4, 26.8, Boxes 25-9, CC-UR, and CC-EA]
- There is a growing body of literature on adaptation practices in both developed and developing country rural areas, including documentation of practical experience in agriculture, water, forestry, and biodiversity and, to a lesser extent, fisheries (*very high confidence*). Public policies supporting decision making for adaptation in rural areas exist in developed and, increasingly, developing countries, and there are also examples of private adaptations led by individuals, companies, and nongovernmental organizations (NGOs) (*high confidence*). Adaptation constraints, particularly pronounced in developing countries, result from lack of access to credit, land, water, technology, markets, information, and perceptions of the need to change. [9.4, 17.3, Tables 9-7 and 9-8]
- In Africa, most national governments are initiating governance systems for adaptation (*high confidence*). Progress on national and subnational policies and strategies has initiated the mainstreaming of adaptation into sectoral planning, but evolving institutional frameworks cannot yet effectively coordinate the range of adaptation initiatives being implemented. Disaster risk management, adjustments in technologies and infrastructure, ecosystem-based approaches, basic public health measures, and livelihood diversification are reducing vulnerability, although efforts to date tend to be isolated. [22.4]
- In Europe, adaptation policy has been developed at international (EU), national, and local government levels, with limited systematic information on current implementation or effectiveness (*high confidence*). Some adaptation planning has been integrated into coastal and water management, into environmental protection and land planning, and into disaster risk management. [23.7, Boxes 5-1 and 23-3]
- In Asia, adaptation is being facilitated in some areas through mainstreaming climate adaptation action into subnational development planning, early warning systems, integrated water resources management, agroforestry, and coastal reforestation of mangroves (*high confidence*). [24.4 to 24.6, 24.9, Box CC-TC]
- In Australasia, planning for sea level rise, and in southern Australia for reduced water availability, is becoming adopted widely. Planning

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Table TS.2 | Illustrative examples of adaptation experience, as well as approaches to reducing vulnerability and enhancing resilience. Adaptation actions can be influenced by climate variability, extremes, and change, and by exposure and vulnerability at the scale of risk management. Many examples and case studies demonstrate complexity at the level of communities or specific regions within a country. It is at this spatial scale that complex interactions between vulnerability, exposure, and climate change come to the fore. [Table 21-4]

Early warning systems for heat	
Exposure and vulnerability	Factors affecting exposure and vulnerability include age, preexisting health status, level of outdoor activity, socioeconomic factors including poverty and social isolation, access to and use of cooling, physiological and behavioral adaptation of the population, urban heat island effects, and urban infrastructure. [8.2.3, 8.2.4, 11.3.3, 11.3.4, 11.4.1, 11.7, 13.2.1, 19.3.2, 23.5.1, 25.3, 25.8.1, SREX Table SPM.1]
Climate information at the global scale	**Observed:** • *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] • *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] **Projected:** *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal time scales. [WGI AR5 12.4.3]
Climate information at the regional scale	**Observed:** • *Likely* that heat wave frequency has increased since 1950 in large parts of Europe, Asia, and Australia. [WGI AR5 2.6.1] • *Medium confidence* in overall increase in heat waves and warm spells in North America since 1960. Insufficient evidence for assessment or spatially varying trends in heat waves or warm spells for South America and most of Africa. [SREX Table 3-2; WGI AR5 2.6.1] **Projected:** • *Likely* that, by the end of the 21st century under Representative Concentration Pathway 8.5 (RCP8.5) in most land regions, a current 20-year high-temperature event will at least double its frequency and in many regions occur every 2 years or annually, while a current 20-year low-temperature event will become exceedingly rare. [WGI AR5 12.4.3] • *Very likely* more frequent and/or longer heat waves or warm spells over most land areas. [WGI AR5 12.4.3]
Description	Heat-health early warning systems are instruments to prevent negative health impacts during heat waves. Weather forecasts are used to predict situations associated with increased mortality or morbidity. Components of effective heat wave and health warning systems include identifying weather situations that adversely affect human health, monitoring weather forecasts, communicating heat wave and prevention responses, targeting notifications to vulnerable populations, and evaluating and revising the system to increase effectiveness in a changing climate. Warning systems for heat waves have been planned and implemented broadly, for example in Europe, the United States, Asia, and Australia. [11.7.3, 24.4.6, 25.8.1, 26.6, Box 25-6]
Broader context	• Heat-health warning systems can be combined with other elements of a health protection plan, for example building capacity to support communities most at risk, supporting and funding health services, and distributing public health information. • In Africa, Asia, and elsewhere, early warning systems have been used to provide warning of and reduce a variety of risks related to famine and food insecurity; flooding and other weather-related hazards; exposure to air pollution from fire; and vector-borne and food-borne disease outbreaks. [7.5.1, 11.7, 15.4.2, 22.4.5, 24.4.6, 25.8.1, 26.6.3, Box 25-6]
Mangrove restoration to reduce flood risks and protect shorelines from storm surge	
Exposure and vulnerability	Loss of mangroves increases exposure of coastlines to storm surge, coastal erosion, saline intrusion, and tropical cyclones. Exposed infrastructure, livelihoods, and people are vulnerable to associated damage. Areas with development in the coastal zone, such as on small islands, can be particularly vulnerable. [5.4.3, 5.5.6, 29.7.2, Box CC-EA]
Climate information at the global scale	**Observed:** • *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5] • *Low confidence* in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. [WGI AR5 2.6.3] **Projected:** • *Very likely* significant increase in the occurrence of future sea level extremes by 2050 and 2100. [WGI AR5 13.7.2] • In the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates. [WGI AR5 14.6]
Climate information at the regional scale	**Observed:** Change in sea level relative to the land (relative sea level) can be significantly different from the global mean sea level change because of changes in the distribution of water in the ocean and vertical movement of the land. [WGI AR5 3.7.3] **Projected:** • *Low confidence* in region-specific projections of storminess and associated storm surges. [WGI AR5 13.7.2] • Projections of regional changes in sea level reach values of up to 30% above the global mean value in the Southern Ocean and around North America, and between 10% to 20% above the global mean value in equatorial regions. [WGI AR5 13.6.5] • *More likely than not* substantial increase in the frequency of the most intense tropical cyclones in the western North Pacific and North Atlantic. [WGI AR5 14.6]
Description	Mangrove restoration and rehabilitation has occurred in a number of locations (e.g., Vietnam, Djibouti, and Brazil) to reduce coastal flooding risks and protect shorelines from storm surge. Restored mangroves have been shown to attenuate wave height and thus reduce wave damage and erosion. They protect aquaculture industry from storm damage and reduce saltwater intrusion. [2.4.3, 5.5.4, 8.3.3, 22.4.5, 27.3.3]
Broader context	• Considered a low-regrets option benefiting sustainable development, livelihood improvement, and human well-being through improvements for food security and reduced risks from flooding, saline intrusion, wave damage, and erosion. Restoration and rehabilitation of mangroves, as well as of wetlands or deltas, is ecosystem-based adaptation that enhances ecosystem services. • Synergies with mitigation given that mangrove forests represent large stores of carbon. • Well-integrated ecosystem-based adaptation can be more cost effective and sustainable than non-integrated physical engineering approaches. [5.5, 8.4.2, 14.3.1, 24.6, 29.3.1, 29.7.2, 30.6.1, 30.6.2, Table 5-4, Box CC-EA]

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Table TS.2 (continued)

Community-based adaptation and traditional practices in small island contexts	
Exposure and vulnerability	With small land area, often low elevation coasts, and concentration of human communities and infrastructure in coastal zones, small islands are particularly vulnerable to rising sea levels and impacts such as inundation, saltwater intrusion, and shoreline change. [29.3.1, 29.3.3, 29.6.1, 29.6.2, 29.7.2]
Climate information at the global scale	**Observed:** • *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5] • *Low confidence* in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. [WGI AR5 2.6.3] • Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] **Projected:** • *Very likely* significant increase in the occurrence of future sea level extremes by 2050 and 2100. [WGI AR5 13.7.2] • In the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates. [WGI AR5 14.6] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** Change in sea level relative to the land (relative sea level) can be significantly different from the global mean sea level change because of changes in the distribution of water in the ocean and vertical movement of the land. [WGI AR5 3.7.3] **Projected:** • *Low confidence* in region-specific projections of storminess and associated storm surges. [WGI AR5 13.7.2] • Projections of regional changes in sea level reach values of up to 30% above the global mean value in the Southern Ocean and around North America, and between 10% and 20% above the global mean value in equatorial regions. [WGI AR5 13.6.5] • *More likely than not* substantial increase in the frequency of the most intense tropical cyclones in the western North Pacific and North Atlantic. [WGI AR5 14.6]
Description	Traditional technologies and skills can be relevant for climate adaptation in small island contexts. In the Solomon Islands, relevant traditional practices include elevating concrete floors to keep them dry during heavy precipitation events and building low aerodynamic houses with palm leaves as roofing to avoid hazards from flying debris during cyclones, supported by perceptions that traditional construction methods are more resilient to extreme weather. In Fiji after Cyclone Ami in 2003, mutual support and risk sharing formed a central pillar for community-based adaptation, with unaffected households fishing to support those with damaged homes. Participatory consultations across stakeholders and sectors within communities and capacity building taking into account traditional practices can be vital to the success of adaptation initiatives in island communities, such as in Fiji or Samoa. [29.6.2]
Broader context	• Perceptions of self-efficacy and adaptive capacity in addressing climate stress can be important in determining resilience and identifying useful solutions. • The relevance of community-based adaptation principles to island communities, as a facilitating factor in adaptation planning and implementation, has been highlighted, for example, with focus on empowerment and learning-by-doing, while addressing local priorities and building on local knowledge and capacity. Community-based adaptation can include measures that cut across sectors and technological, social, and institutional processes, recognizing that technology by itself is only one component of successful adaptation. [5.5.4, 29.6.2]
Adaptive approaches to flood defense in Europe	
Exposure and vulnerability	Increased exposure of persons and property in flood risk areas has contributed to increased damages from flood events over recent decades. [5.4.3, 5.4.4, 5.5.5, 23.3.1, Box 5-1]
Climate information at the global scale	**Observed:** • *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5] • Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] **Projected:** • *Very likely* that the time-mean rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971–2010 for all RCP scenarios. [WGI AR5 13.5.1] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** • *Likely* increase in the frequency or intensity of heavy precipitation in Europe, with some seasonal and/or regional variations. [WGI AR5 2.6.2] • Increase in heavy precipitation in winter since the 1950s in some areas of northern Europe (*medium confidence*). Increase in heavy precipitation since the 1950s in some parts of west-central Europe and European Russia, especially in winter (*medium confidence*). [SREX Table 3-2] • Increasing mean sea level with regional variations, except in the Baltic Sea where the relative sea level is decreasing due to vertical crustal motion. [5.3.2, 23.2.2] **Projected:** • Over most of the mid-latitude land masses, extreme precipitation events will *very likely* be more intense and more frequent in a warmer world. [WGI AR5 12.4.5] • Overall precipitation increase in northern Europe and decrease in southern Europe (*medium confidence*). [23.2.2] • Increased extreme precipitation in northern Europe during all seasons, particularly winter, and in central Europe except in summer (*high confidence*). [23.2.2; SREX Table 3-3]
Description	Several governments have made ambitious efforts to address flood risk and sea level rise over the coming century. In the Netherlands, government recommendations include "soft" measures preserving land from development to accommodate increased river inundation; maintaining coastal protection through beach nourishment; and ensuring necessary political-administrative, legal, and financial resources. Through a multi-stage process, the British government has also developed extensive adaptation plans to adjust and improve flood defenses to protect London from future storm surges and river flooding. Pathways have been analyzed for different adaptation options and decisions, depending on eventual sea level rise, with ongoing monitoring of the drivers of risk informing decisions. [5.5.4, 23.7.1, Box 5-1]
Broader context	• The Dutch plan is considered a paradigm shift, addressing coastal protection by "working with nature" and providing "room for river." • The British plan incorporates iterative, adaptive decisions depending on the eventual sea level rise with numerous and diverse measures possible over the next 50 to 100 years to reduce risk to acceptable levels. • In cities in Europe and elsewhere, the importance of strong political leadership or government champions in driving successful adaptation action has been noted. [5.5.3, 5.5.4, 8.4.3, 23.7.1, 23.7.2, 23.7.4, Boxes 5-1 and 26-3]

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Table TS.2 (continued)

Index-based insurance for agriculture in Africa	
Exposure and vulnerability	Susceptibility to food insecurity and depletion of farmers' productive assets following crop failure. Low prevalence of insurance due to absent or poorly developed insurance markets or to amount of premium payments. The most marginalized and resource-poor especially may have limited ability to afford insurance premiums. [10.7.6, 13.3.2, Box 22-1]
Climate information at the global scale	**Observed:** • *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] • *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] • Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] • *Low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall). [WGI AR5 2.6.2] **Projected:** • *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal time scales. [WGI AR5 12.4.3] • Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions, and are projected with *medium confidence* by the end of this century under the RCP8.5 scenario. [WGI AR5 12.4.5] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** • *Medium confidence* in increase in frequency of warm days and decrease in frequency of cold days and nights in southern Africa. [SREX Table 3-2] • *Medium confidence* in increase in frequency of warm nights in northern and southern Africa. [SREX Table 3-2] **Projected:** • *Likely* surface drying in southern Africa by the end of the 21st century under RCP8.5 (*high confidence*). [WGI AR5 12.4.5] • *Likely* increase in warm days and nights and decrease in cold days and nights in all regions of Africa (*high confidence*). Increase in warm days largest in summer and fall (*medium confidence*). [SREX Table 3-3] • *Likely* more frequent and/or longer heat waves and warm spells in Africa (*high confidence*). [SREX Table 3-3]
Description	A recently introduced mechanism that has been piloted in a number of rural locations, including in Malawi, Sudan, and Ethiopia, as well as in India. When physical conditions reach a particular predetermined threshold where significant losses are expected to occur—weather conditions such as excessively high or low cumulative rainfall or temperature peaks—the insurance pays out. [9.4.2, 13.3.2, 15.4.4, Box 22-1]
Broader context	• Index-based weather insurance is considered well suited to the agricultural sector in developing countries. • The mechanism allows risk to be shared across communities, with costs spread over time, while overcoming obstacles to traditional agricultural and disaster insurance markets. It can be integrated with other strategies such as microfinance and social protection programs. • Risk-based premiums can help encourage adaptive responses and foster risk awareness and risk reduction by providing financial incentives to policyholders to reduce their risk profile. • Challenges can be associated with limited availability of accurate weather data and difficulties in establishing which weather conditions cause losses. Basis risk (i.e., farmers suffer losses but no payout is triggered based on weather data) can promote distrust. There can also be difficulty in scaling up pilot schemes. • Insurance for work programs can enable cash-poor farmers to work for insurance premiums by engaging in community-identified disaster risk reduction projects. [10.7.4 to 10.7.6, 13.3.2, 15.4.4, Table 10-7, Boxes 22-1 and 25-7]

Continued next page →

for sea level rise has evolved considerably over the past 2 decades and shows a diversity of approaches, although its implementation remains piecemeal (*high confidence*). Adaptive capacity is generally high in many human systems, but implementation faces major constraints especially for transformational responses at local and community levels. [25.4, 25.10, Table 25-2, Boxes 25-1, 25-2, and 25-9]

- In North America, governments are engaging in incremental adaptation assessment and planning, particularly at the municipal level (*high confidence*). Some proactive adaptation is occurring to protect longer-term investments in energy and public infrastructure. [26.7 to 26.9]
- In Central and South America, ecosystem-based adaptation including protected areas, conservation agreements, and community management of natural areas is occurring (*high confidence*). Resilient crop varieties, climate forecasts, and integrated water resources management are being adopted within the agricultural sector in some areas. [27.3]
- In the Arctic, some communities have begun to deploy adaptive co-management strategies and communications infrastructure, combining traditional and scientific knowledge (*high confidence*). [28.2, 28.4]
- In small islands, which have diverse physical and human attributes, community-based adaptation has been shown to generate larger benefits when delivered in conjunction with other development activities (*high confidence*). [29.3, 29.6, Table 29-3, Figure 29-1]
- In both the open ocean and coastal areas, international cooperation and marine spatial planning are starting to facilitate adaptation to climate change, with constraints from challenges of spatial scale and governance issues (*high confidence*). Observed coastal adaptation includes major projects (e.g., Thames Estuary, Venice Lagoon, Delta Works) and specific practices in some countries (e.g., Netherlands, Australia, Bangladesh). [5.5, 7.3, 15.4, 30.6, Box CC-EA]

Table TS.2 presents examples of how climate extremes and change, as well as exposure and vulnerability at the scale of risk management, shape adaptation actions and approaches to reducing vulnerability and enhancing resilience.

A-3. The Decision-making Context

Climate variability and extremes have long been important in many decision-making contexts. Climate-related risks are now evolving over

Table TS.2 (continued)

Relocation of agricultural industries in Australia	
Exposure and vulnerability	Crops sensitive to changing patterns of temperature, rainfall, and water availability. [7.3, 7.5.2]
Climate information at the global scale	**Observed:** • *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] • *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] • *Medium confidence* in precipitation change over global land areas since 1950. [WGI AR5 2.5.1] • Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] • *Low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall). [WGI AR5 2.6.2] **Projected:** • *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal time scales. [WGI AR5 12.4.3] • *Virtually certain* increase in global precipitation as global mean surface temperature increases. [WGI AR5 12.4.1] • Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions, and are projected with *medium confidence* by the end of this century under the RCP8.5 scenario. [WGI AR5 12.4.5] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** • Cool extremes rarer and hot extremes more frequent and intense over Australia and New Zealand, since 1950 (*high confidence*). [Table 25-1] • *Likely* increase in heat wave frequency since 1950 in large parts of Australia. [WGI AR5 2.6.1] • Late autumn/winter decreases in precipitation in southwestern Australia since the 1970s and southeastern Australia since the mid-1990s, and annual increases in precipitation in northwestern Australia since the 1950s (*very high confidence*). [Table 25-1] • Mixed or insignificant trends in annual daily precipitation extremes, but a tendency to significant increase in annual intensity of heavy precipitation in recent decades for sub-daily events in Australia (*high confidence*). [Table 25-1] **Projected:** • Hot days and nights more frequent and cold days and nights less frequent during the 21st century in Australia and New Zealand (*high confidence*). [Table 25-1] • Annual decline in precipitation over southwestern Australia (*high confidence*) and elsewhere in southern Australia (*medium confidence*). Reductions strongest in the winter half-year (*high confidence*). [Table 25-1] • Increase in most regions in the intensity of rare daily rainfall extremes and in sub-daily extremes (*medium confidence*) in Australia and New Zealand. [Table 25-1] • Drought occurrence to increase in southern Australia (*medium confidence*). [Table 25-1] • Snow depth and snow area to decline in Australia (*very high confidence*). [Table 25-1] • Freshwater resources projected to decline in far southeastern and far southwestern Australia (*high confidence*). [25.5.2]
Description	Industries and individual farmers are relocating parts of their operations, for example for rice, wine, or peanuts in Australia, or are changing land use *in situ* in response to recent climate change or expectations of future change. For example, there has been some switching from grazing to cropping in southern Australia. Adaptive movement of crops has also occurred elsewhere. [7.5.1, 25.7.2, Table 9-7, Box 25-5]
Broader context	• Considered transformational adaptation in response to impacts of climate change. • Positive or negative implications for the wider communities in origin and destination regions. [25.7.2, Box 25-5]

time due to both climate change and development. This section builds from existing experience with decision making and risk management. It creates a foundation for understanding the report's assessment of future climate-related risks and potential responses.

Responding to climate-related risks involves decision making in a changing world, with continuing uncertainty about the severity and timing of climate-change impacts and with limits to the effectiveness of adaptation (*high confidence*). Iterative risk management is a useful framework for decision making in complex situations characterized by large potential consequences, persistent uncertainties, long timeframes, potential for learning, and multiple climatic and non-climatic influences changing over time. See Figure TS.4. Assessment of the widest possible range of potential impacts, including low-probability outcomes with large consequences, is central to understanding the benefits and trade-offs of alternative risk management actions. The complexity of adaptation actions across scales and contexts means that monitoring and learning are important components of effective adaptation. [2.1 to 2.4, 3.6, 14.1 to 14.3, 15.2 to 15.4, 16.2 to 16.4, 17.1 to 17.3, 17.5, 20.6, 22.4, 25.4, Figure 1-5]

Adaptation and mitigation choices in the near term will affect the risks of climate change throughout the 21st century (*high confidence*). Figure TS.5 illustrates projected climate futures under a low-emission mitigation scenario and a high-emission scenario [Representative Concentration Pathways (RCPs) 2.6 and 8.5], along with observed temperature and precipitation changes. The benefits of adaptation and mitigation occur over different but overlapping timeframes. Projected global temperature increase over the next few decades is similar across emission scenarios (Figure TS.5A, middle panel) (WGI AR5 Section 11.3). During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate. Societal responses, particularly adaptations, will influence near-term outcomes. In the second half of the 21st century and beyond, global temperature increase diverges across emission scenarios (Figure TS.5A, middle and bottom panels) (WGI AR5 Section 12.4 and Table SPM.2). For this longer-term era of climate options, near-term and longer-term adaptation and mitigation, as well as development pathways, will determine the risks of climate change. [2.5, 21.2, 21.3, 21.5, Box CC-RC]

Assessment of risks in the WGII AR5 relies on diverse forms of evidence. Expert judgment is used to integrate evidence into evaluations of risks. Forms of evidence include, for example, empirical observations, experimental results, process-based understanding, statistical approaches, and simulation and descriptive models. Future

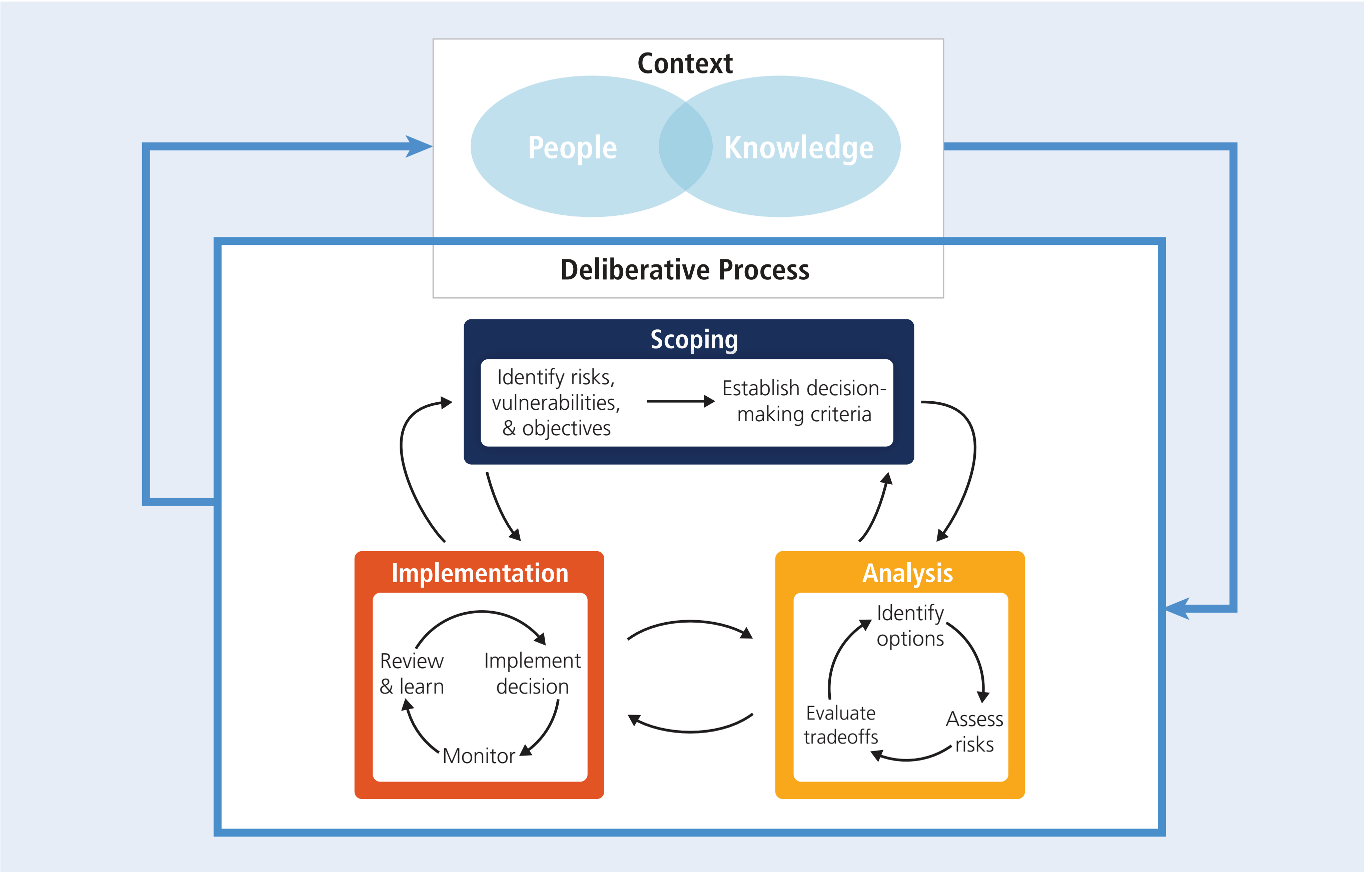

Figure TS.4 | Climate-change adaptation as an iterative risk management process with multiple feedbacks. People and knowledge shape the process and its outcomes. [Figure 2-1]

risks related to climate change vary substantially across plausible alternative development pathways, and the relative importance of development and climate change varies by sector, region, and time period (*high confidence*). Scenarios are useful tools for characterizing possible future socioeconomic pathways, climate change and its risks, and policy implications. Climate-model projections informing evaluations of risks in this report are generally based on the RCPs (Figure TS.5), as well as the older IPCC *Special Report on Emissions Scenarios* (SRES) scenarios. [1.1, 1.3, 2.2, 2.3, 19.6, 20.2, 21.3, 21.5, 26.2, Box CC-RC; WGI AR5 Box SPM.1]

Scenarios can be divided into those that explore how futures may unfold under various drivers (problem exploration) and those that test how various interventions may play out (solution exploration) (*robust evidence*, *high agreement*). Adaptation approaches address uncertainties associated with future climate and socioeconomic conditions and with the diversity of specific contexts (*medium evidence*, *high agreement*). Although many national studies identify a variety of strategies and approaches for adaptation, they can be classified into two broad categories: "top-down" and "bottom-up" approaches. The top-down approach is a scenario-impact approach, consisting of downscaled climate projections, impact assessments, and formulation of strategies and options. The bottom-up approach is a vulnerability-threshold approach, starting with the identification of vulnerabilities, sensitivities, and thresholds for specific sectors or communities. Iterative assessments of impacts and adaptation in the top-down approach and building adaptive capacity of local communities are typical strategies for responding to uncertainties. [2.2, 2.3, 15.3]

Uncertainties about future vulnerability, exposure, and responses of interlinked human and natural systems are large (*high confidence*). This motivates exploration of a wide range of socioeconomic futures in assessments of risks. Understanding future vulnerability, exposure, and response capacity of interlinked human and natural systems is challenging due to the number of interacting social, economic, and cultural factors, which have been incompletely considered to date. These factors include wealth and its distribution across society, demographics, migration, access to technology and information, employment patterns, the quality of adaptive responses, societal values, governance structures, and institutions to resolve conflicts. International dimensions such as trade and relations among states are also important for understanding the risks of climate change at regional scales. [11.3, 12.6, 21.3 to 21.5, 25.3, 25.4, 25.11, 26.2]

(A)

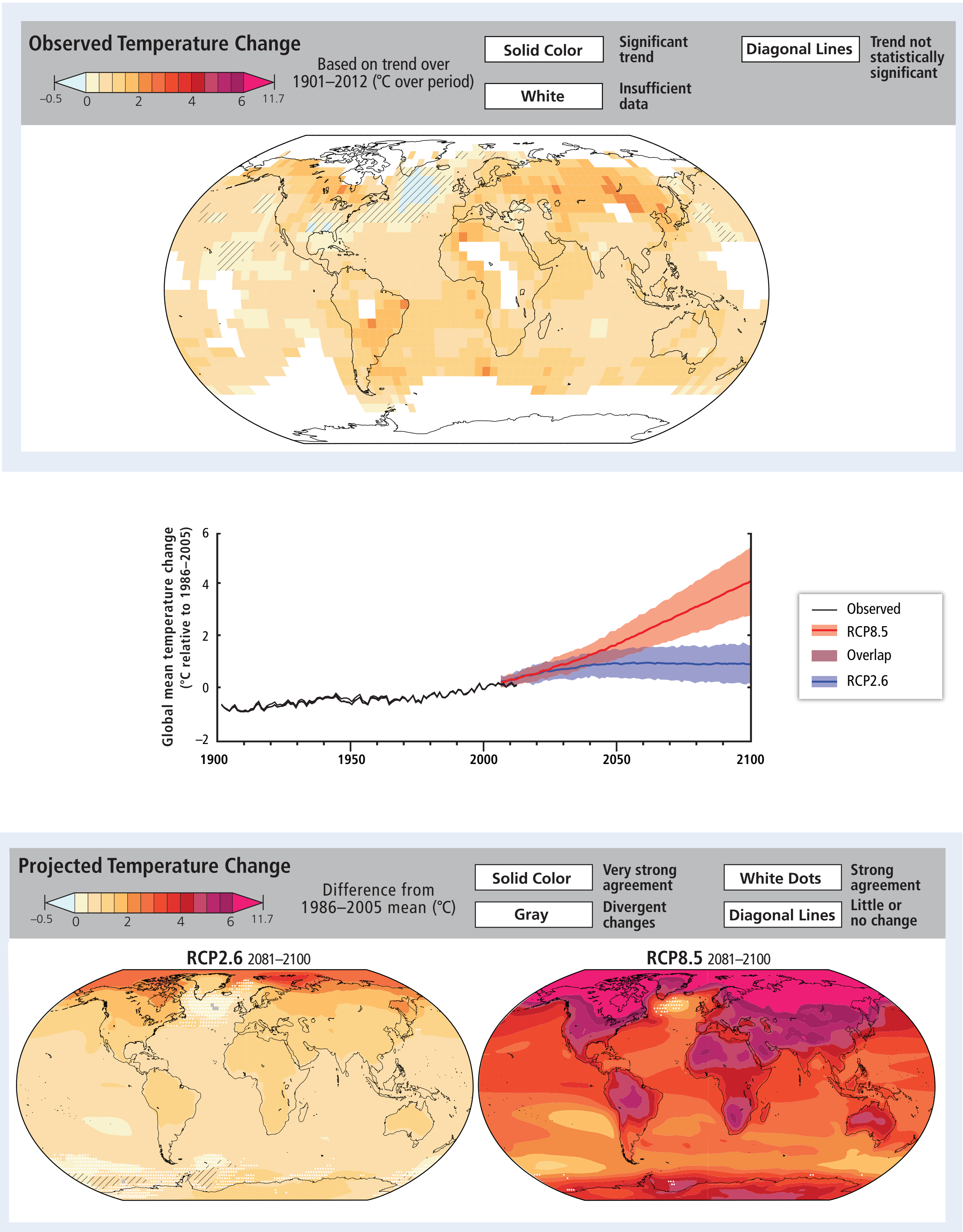

Figure TS.5

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Figure TS.5 (continued)

(B)

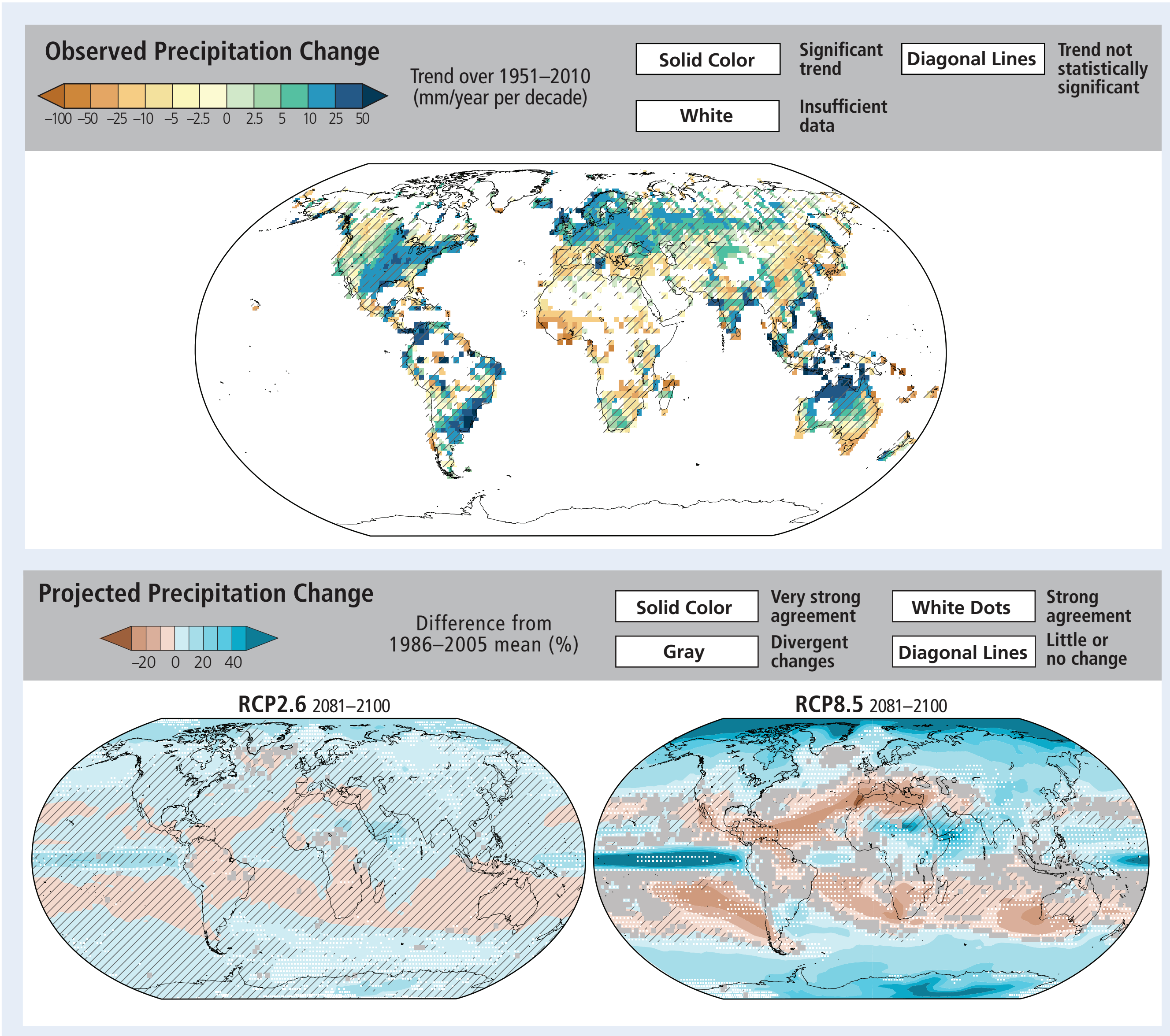


Figure TS.5 | Observed and projected changes in annual average surface temperature (A) and precipitation (B). This figure informs understanding of climate-related risks in the WGII AR5. It illustrates changes observed to date and projected changes under continued high emissions and under ambitious mitigation.

Technical details: (A, top panel) Map of observed annual mean temperature change from 1901–2012, derived from a linear trend. Observed data (range of grid-point values: –0.53 to 2.50°C over period) are from WGI AR5 Figures SPM.1 and 2.21. (B, top panel) Map of observed annual precipitation change from 1951–2010, derived from a linear trend. Observed data (range of grid-point values: –185 to 111 mm/year per decade) are from WGI AR5 Figures SPM.2 and 2.29. For observed temperature and precipitation, trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. (A, middle panel) Observed and projected future global annual mean temperature relative to 1986–2005. Observed warming from 1850–1900 to 1986–2005 is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C). Black lines show temperature estimates from three datasets. Blue and red lines and shading denote the ensemble mean and ±1.64 standard deviation range, based on Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations from 32 models for RCP2.6 and 39 models for RCP8.5. (A and B, bottom panel) CMIP5 multi-model mean projections of annual mean temperature changes (A) and mean percent changes in annual mean precipitation (B) for 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. For temperature projections, analysis uses model data (range of grid-point values across RCP2.6 and 8.5: 0.06 to 11.71°C) from WGI AR5 Figure SPM.8. For precipitation projections, analysis uses model data (range of grid-point values: –9 to 22% for RCP2.6 and –34 to 112% for RCP8.5) from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. For a full description of methods, see Box CC-RC. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC; WGI AR5 2.4 and 2.5, Figures SPM.1, SPM.2, SPM.7, SPM.8, 2.21, and 2.29]

B: FUTURE RISKS AND OPPORTUNITIES FOR ADAPTATION

This section presents future risks and more limited potential benefits across sectors and regions, examining how they are affected by the magnitude and rate of climate change and by socioeconomic choices. It also assesses opportunities for reducing impacts and managing risks through adaptation and mitigation. The section examines the distribution of risks across populations with contrasting vulnerability and adaptive capacity, across sectors where metrics for quantifying impacts may be quite different, and across regions with varying traditions and resources. The assessment features interactions across sectors and regions and among climate change and other stressors. For different sectors and regions, the section describes risks and potential benefits over the next few decades, the near-term era of committed climate change. Over this timeframe, projected global temperature increase is similar across emission scenarios. The section also provides information on risks and potential benefits in the second half of the 21st century and beyond, the longer-term era of climate options. Over this longer term, global temperature increase diverges across emission scenarios, and the assessment distinguishes potential outcomes for 2°C and 4°C global mean temperature increase above preindustrial levels. The section elucidates how and when choices matter in reducing future risks, highlighting the differing timeframes for mitigation and adaptation benefits.

B-1. Key Risks across Sectors and Regions

Key risks are potentially severe impacts relevant to Article 2 of the UN Framework Convention on Climate Change, which refers to "dangerous anthropogenic interference with the climate system." Risks are considered key due to high hazard or high vulnerability of societies and systems exposed, or both. Identification of key risks was based on expert judgment using the following specific criteria: large magnitude, high probability, or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation. Key risks are integrated into five complementary and overarching reasons for concern (RFCs) in Box TS.5.

The key risks that follow, all of which are identified with *high confidence*, span sectors and regions. Each of these key risks contributes to one or more RFCs. Roman numerals correspond to entries in Table TS.3, which further illustrates relevant examples and interactions. [19.2 to 19.4, 19.6, Table 19-4, Boxes 19-2 and CC-KR]

i) Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise. See RFCs 1 to 5. [5.4, 8.2, 13.2, 19.2 to 19.4, 19.6, 19.7, 24.4, 24.5, 26.7, 26.8, 29.3, 30.3, Tables 19-4 and 26-1, Figure 26-2, Boxes 25-1, 25-7, and CC-KR]

Table TS.3 | A selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in chapters of this report. The examples underscore the complexity of risks determined by various interacting climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities (see also Figure TS.1). Vulnerabilities identified as key arise when exposure to hazards combines with social, institutional, economic, or environmental vulnerability, as indicated by icons in the table. Emergent risks arise from complex system interactions. Roman numerals correspond with key risks listed in Section B-1. [19.6, Table 19-4]

No.	Hazard	Key vulnerabilities	Key risks	Emergent risks
i	Sea level rise and coastal flooding including storm surges [5.4.3, 8.1.4, 8.2.3, 8.2.4, 13.1.4, 13.2.2, 24.4, 24.5, 26.7, 26.8, 29.3, 30.3.1, Boxes 25-1 and 25-7; WGI AR5 3.7, 13.5, Table 13-5]	High exposure of people, economic activity, and infrastructure in low-lying coastal zones and Small Island Developing States (SIDS) and other small islands Urban population unprotected due to substandard housing and inadequate insurance. Marginalized rural population with multidimensional poverty and limited alternative livelihoods Insufficient local governmental attention to disaster risk reduction	Death, injury, and disruption to livelihoods, food supplies, and drinking water Loss of common-pool resources, sense of place, and identity, especially among indigenous populations in rural coastal zones	Interaction of rapid urbanization, sea level rise, increasing economic activity, disappearance of natural resources, and limits of insurance; burden of risk management shifted from the state to those at risk leading to greater inequality
ii	Extreme precipitation and inland flooding [3.2.7, 3.4.8, 8.2.3, 8.2.4, 13.2.1, 25.10, 26.3, 26.7, 26.8, 27.3.5, Box 25-8; WGI AR5 11.3.2]	Large numbers of people exposed in urban areas to flood events, particularly in low-income informal settlements Overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure and limited ability to cope and adapt due to marginalization, high poverty, and culturally imposed gender roles Inadequate governmental attention to disaster risk reduction	Death, injury, and disruption of human security, especially among children, elderly, and disabled persons	Interaction of increasing frequency of intense precipitation, urbanization, and limits of insurance; burden of risk management shifted from the state to those at risk leading to greater inequality, eroded assets due to infrastructure damage, abandonment of urban districts, and the creation of high risk/high poverty spatial traps
iii	Novel hazards yielding systemic risks [8.1.4, 8.2.4, 10.2, 10.3, 12.6, 23.9, 25.10, 26.7, 26.8; WGI AR5 11.3.2]	Populations and infrastructure exposed and lacking historical experience with these hazards Overly hazard-specific management planning and infrastructure design, and/or low forecasting capability	Failure of systems coupled to electric power system, e.g., drainage systems reliant on electric pumps or emergency services reliant on telecommunications. Collapse of health and emergency services in extreme events	Interactions due to dependence on coupled systems lead to magnification of impacts of extreme events. Reduced social cohesion due to loss of faith in management institutions undermines preparation and capacity for response.
iv	Increasing frequency and intensity of extreme heat, including urban heat island effect [8.2.3, 11.3, 11.4.1, 13.2, 23.5.1, 24.4.6, 25.8.1, 26.6, 26.8, Box CC-HS; WGI AR5 11.3.2]	Increasing urban population of the elderly, the very young, expectant mothers, and people with chronic health problems in settlements subject to higher temperatures Inability of local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups	Increased mortality and morbidity during periods of extreme heat	Interaction of demographic shifts with changes in regional temperature extremes, local heat island, and air pollution Overloading of health and emergency services. Higher mortality, morbidity, and productivity loss among manual workers in hot climates

Table TS.3 (continued)

No.	Hazard	Key vulnerabilities	Key risks	Emergent risks
v	Warming, drought, and precipitation variability [7.3 to 7.5, 11.3, 11.6.1, 13.2, 19.3.2, 19.4.1, 22.3.4, 24.4, 26.8, 27.3.4; WGI AR5 11.3.2]	Poorer populations in urban and rural settings are susceptible to resulting food insecurity; includes particularly farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers. Limited ability to cope among the elderly and female-headed households	Risk of harm and loss of life due to reversal of progress in reducing malnutrition	Interactions of climate changes, population growth, reduced productivity, biofuel crop cultivation, and food prices with persistent inequality, and ongoing food insecurity for the poor increase malnutrition, giving rise to larger burden of disease. Exhaustion of social networks reduces coping capacity.
vi	Drought [3.2.7, 3.4.8, 3.5.1, 8.2.3, 8.2.4, 9.3.3, 9.3.5, 13.2.1, 19.3.2, 24.4, 25.7, Box 25-5; WGI AR5 12.4.1, 12.4.5]	Urban populations with inadequate water services. Existing water shortages (and irregular supplies), and constraints on increasing supplies Lack of capacity and resilience in water management regimes including rural–urban linkages	Insufficient water supply for people and industry yielding severe harm and economic impacts	Interaction of urbanization, infrastructure insufficiency, groundwater depletion
		Poorly endowed farmers in drylands or pastoralists with insufficient access to drinking and irrigation water Limited ability to compensate for losses in water-dependent farming and pastoral systems, and conflict over natural resources Lack of capacity and resilience in water management regimes, inappropriate land policy, and misperception and undermining of pastoral livelihoods	Loss of agricultural productivity and/or income of rural people. Destruction of livelihoods particularly for those depending on water-intensive agriculture. Risk of food insecurity	Interactions across human vulnerabilities: deteriorating livelihoods, poverty traps, heightened food insecurity, decreased land productivity, rural outmigration, and increase in new urban poor in developing countries. Potential tipping point in rain-fed farming system and/or pastoralism
vii	Rising ocean temperature, ocean acidification, and loss of Arctic sea ice [5.4.2, 6.3.1, 6.3.2, 7.4.2, 9.3.5, 22.3.2, 24.4, 25.6, 27.3.3, 28.2, 28.3, 29.3.1, 30.5, 30.6, Boxes CC-OA and CC-CR; WGI AR5 11.3.3]	High susceptibility of warm-water coral reefs and respective ecosystem services for coastal communities; high susceptibility of polar systems, e.g., to invasive species Susceptibility of coastal and SIDS fishing communities depending on these ecosystem services; and of Arctic settlements and culture	Loss of coral cover, Arctic species, and associated ecosystems with reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms	Interactions of stressors such as acidification and warming on calcareous organisms enhancing risk
viii	Rising land temperatures, and changes in precipitation patterns and in frequency and intensity of extreme heat [4.3.4, 19.3.2, 22.4.5, 27.3, Boxes 23-1 and CC-WE; WGI AR5 11.3.2]	Susceptibility of human systems, agro-ecosystems, and natural ecosystems to (1) loss of regulation of pests and diseases, fire, landslide, erosion, flooding, avalanche, water quality, and local climate; (2) loss of provision of food, livestock, fiber, and bioenergy; (3) loss of recreation, tourism, aesthetic and heritage values, and biodiversity	Reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms	Interaction of social-ecological systems with loss of ecosystem services on which they depend

Social vulnerability · Economic vulnerability · Environmental vulnerability · Institutional vulnerability · Exposure

ii) Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions. See RFCs 2 and 3. [3.4, 3.5, 8.2, 13.2, 19.6, 25.10, 26.3, 26.8, 27.3, Tables 19-4 and 26-1, Boxes 25-8 and CC-KR]

iii) Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services. See RFCs 2 to 4. [5.4, 8.1, 8.2, 9.3, 10.2, 10.3, 12.6, 19.6, 23.9, 25.10, 26.7, 26.8, 28.3, Table 19-4, Boxes CC-KR and CC-HS]

iv) Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas. See RFCs 2 and 3. [8.1, 8.2, 11.3, 11.4, 11.6, 13.2, 19.3, 19.6, 23.5, 24.4, 25.8, 26.6, 26.8, Tables 19-4 and 26-1, Boxes CC-KR and CC-HS]

v) Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings. See RFCs 2 to 4. [3.5, 7.4, 7.5, 8.2, 8.3, 9.3, 11.3, 11.6, 13.2, 19.3, 19.4, 19.6, 22.3, 24.4, 25.5, 25.7, 26.5, 26.8, 27.3, 28.2, 28.4, Table 19-4, Box CC-KR]

vi) Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions. See RFCs 2 and 3. [3.4, 3.5, 9.3, 12.2, 13.2, 19.3, 19.6, 24.4, 25.7, 26.8, Table 19-4, Boxes 25-5 and CC-KR]

vii) Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the

Box TS.5 | Human Interference with the Climate System

Human influence on the climate system is clear (WGI AR5 SPM Section D.3; WGI AR5 Sections 2.2, 6.3, 10.3 to 10.6, 10.9). Yet determining whether such influence constitutes "dangerous anthropogenic interference" in the words of Article 2 of the UNFCCC involves both risk assessment and value judgments. Scientific assessment can characterize risks based on the likelihood, magnitude, and scope of potential consequences of climate change. Science can also evaluate risks varying spatially and temporally across alternative development pathways, which affect vulnerability, exposure, and level of climate change. Interpreting the potential danger of risks, however, also requires value judgments by people with differing goals and worldviews. Judgments about the risks of climate change depend on the relative importance ascribed to economic versus ecosystem assets, to the present versus the future, and to the distribution versus aggregation of impacts. From some perspectives, isolated or infrequent impacts from climate change may not rise to the level of dangerous anthropogenic interference, but accumulation of the same kinds of impacts could, as they become more widespread, more frequent, or more severe. The rate of climate change can also influence risks. This report assesses risks across contexts and through time, providing a basis for judgments about the level of climate change at which risks become dangerous.

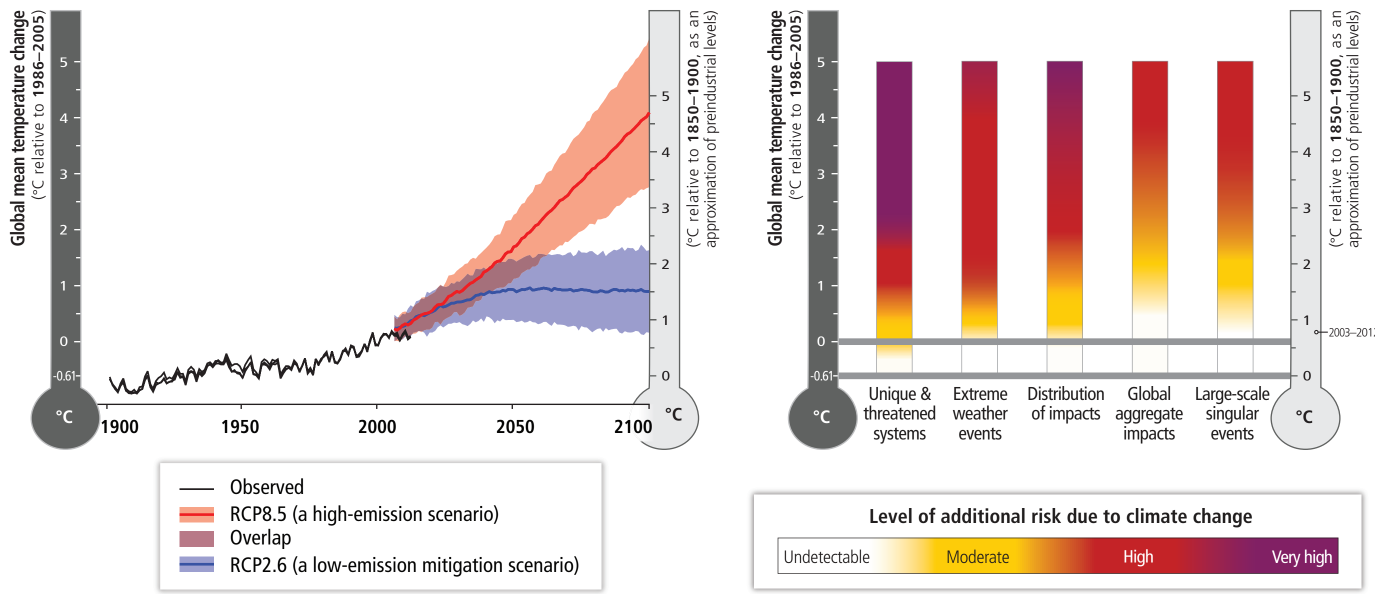
Five integrative reasons for concern (RFCs) provide a framework for summarizing key risks across sectors and regions. First identified in the IPCC Third Assessment Report, the RFCs illustrate the implications of warming and of adaptation limits for people, economies, and ecosystems. They provide one starting point for evaluating dangerous anthropogenic interference with the climate system. Risks for each RFC, updated based on assessment of the literature and expert judgments, are presented below and in Box TS.5 Figure 1. All temperatures below are given as global average temperature change relative to 1986–2005 ("recent").[1] [18.6, 19.6]

1) **Unique and threatened systems**: Some unique and threatened systems, including ecosystems and cultures, are already at risk from climate change (*high confidence*). The number of such systems at risk of severe consequences is higher with additional warming of around 1°C. Many species and systems with limited adaptive capacity are subject to very high risks with additional warming of 2°C, particularly Arctic-sea-ice and coral-reef systems.
2) **Extreme weather events**: Climate-change-related risks from extreme events, such as heat waves, extreme precipitation, and coastal flooding, are already moderate (*high confidence*) and high with 1°C additional warming (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures (*high confidence*).
3) **Distribution of impacts**: Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Risks are already moderate because of regionally differentiated climate-change impacts on crop production in particular (*medium* to *high confidence*). Based on projected decreases in regional crop yields and water availability, risks of unevenly distributed impacts are high for additional warming above 2°C (*medium confidence*).
4) **Global aggregate impacts**: Risks of global aggregate impacts are moderate for additional warming between 1–2°C, reflecting impacts to both Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss with associated loss of ecosystem goods and services results in high risks around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above.
5) **Large-scale singular events**: With increasing warming, some physical systems or ecosystems may be at risk of abrupt and irreversible changes. Risks associated with such tipping points become moderate between 0–1°C additional warming, due to early warning signs that both warm-water coral reef and Arctic ecosystems are already experiencing irreversible regime shifts (*medium confidence*). Risks increase disproportionately as temperature increases between 1–2°C additional warming and become high above 3°C, due to the potential for a large and irreversible sea level rise from ice sheet loss. For sustained warming greater than some threshold,[2] near-complete loss of the Greenland ice sheet would occur over a millennium or more, contributing up to 7 m of global mean sea level rise.

Continued next page →

1 Observed warming from 1850–1900 to 1986–2005 is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C). [WGI AR5 2.4]

2 Current estimates indicate that this threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) sustained global mean warming above preindustrial levels. [WGI AR5 SPM, 5.8, 13.4, 13.5]



Box TS.5 Figure 1 | A global perspective on climate-related risks. Risks associated with reasons for concern are shown at right for increasing levels of climate change. The color shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. Undetectable risk (white) indicates no associated impacts are detectable and attributable to climate change. Moderate risk (yellow) indicates that associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks. High risk (red) indicates severe and widespread impacts, also accounting for the other specific criteria for key risks. Purple, introduced in this assessment, shows that very high risk is indicated by all specific criteria for key risks. [Figure 19-4] For reference, past and projected global annual average surface temperature is shown at left, as in Figure TS.5. [Figure RC-1, Box CC-RC; WGI AR5 Figures SPM.1 and SPM.7] Based on the longest global surface temperature dataset available, the observed change between the average of the period 1850–1900 and of the AR5 reference period (1986–2005) is 0.61°C (5–95% confidence interval: 0.55 to 0.67°C) [WGI AR5 SPM, 2.4], which is used here as an approximation of the change in global mean surface temperature since preindustrial times, referred to as the period before 1750. [WGI and WGII AR5 glossaries]

Arctic. See RFCs 1, 2, and 4. [5.4, 6.3, 7.4, 9.3, 19.5, 19.6, 22.3, 25.6, 27.3, 28.2, 28.3, 29.3, 30.5 to 30.7, Table 19-4, Boxes CC-OA, CC-CR, CC-KR, and CC-HS]

viii) Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods. See RFCs 1, 3, and 4. [4.3, 9.3, 19.3 to 19.6, 22.3, 25.6, 27.3, 28.2, 28.3, Table 19-4, Boxes CC-KR and CC-WE]

Many key risks constitute particular challenges for the least developed countries and vulnerable communities, given their limited ability to cope.

Increasing magnitudes of warming increase the likelihood of severe, pervasive, and irreversible impacts. Some risks of climate change are considerable at 1°C or 2°C above preindustrial levels (as shown in Box TS.5). Global climate change risks are high to very high with global mean temperature increase of 4°C or more above preindustrial levels in all reasons for concern (Box TS.5), and include severe and widespread impacts on unique and threatened systems, substantial species extinction, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year (*high confidence*). See Box TS.6. The precise levels of climate change sufficient to trigger tipping points (thresholds for abrupt and irreversible change) remain uncertain, but the risk associated with crossing multiple tipping points in the earth system or in interlinked human and natural systems increases with rising temperature (*medium confidence*). [4.2, 4.3, 11.8, 19.5, 19.7, 26.5, Box CC-HS]

The overall risks of climate change impacts can be reduced by limiting the rate and magnitude of climate change. Risks are reduced substantially under the assessed scenario with the lowest temperature projections (RCP2.6 – low emissions) compared to the highest temperature projections (RCP8.5 – high emissions), particularly in the second half of the 21st century (*very high confidence*). Examples include reduced risk of negative agricultural yield impacts; of water scarcity; of major challenges to urban settlements and infrastructure from sea level rise; and of adverse impacts from heat extremes, floods, and droughts in areas where increased occurrence of these extremes is projected. Reducing climate change can also reduce the scale of adaptation that might be required. Under all assessed scenarios for adaptation and mitigation, some risk from adverse impacts remains (*very high confidence*). Because mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades, but adaptation cannot generally overcome all climate change effects. In addition to biophysical limits to adaptation for example under high temperatures, some adaptation options will be too costly or resource intensive or will be cost ineffective until climate change effects grow to merit investment costs (*high confidence*). Some mitigation or adaptation options also pose risks. [3.4, 3.5, 4.2, 4.4, 16.3, 16.6, 17.2, 19.7, 20.3, 22.4, 22.5, 25.10, Tables 3-2, 8-3, and 8-6, Boxes 16-3 and 25-1]

B-2. Sectoral Risks and Potential for Adaptation

For the near-term era of committed climate change (the next few decades) and the longer-term era of climate options (the second half

Box TS.6 | Consequences of Large Temperature Increase

This box provides a selection of salient climate change impacts projected for large temperature rise. Warming levels described here (e.g., 4°C warming) refer to global mean temperature increase above preindustrial levels, unless otherwise indicated.

With 4°C warming, climate change is projected to become an increasingly important driver of impacts on ecosystems, becoming comparable with land-use change. [4.2, 19.5] A number of studies project large increases in water stress, groundwater supplies, and drought in a number of regions with greater than 4°C warming, and decreases in others, generally placing already arid regions at greater water stress. [19.5]

Risks of large-scale singular events such as ice sheet disintegration, methane release from clathrates, and onset of long-term droughts in areas such as southwest North America [19.6, Box 26-1; WGI AR5 12.4, 12.5, 13.4], as well as regime shifts in ecosystems and substantial species loss [4.3, 19.6], are higher with increased warming. Sustained warming greater than some threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea level rise of up to 7 m (*high confidence*); current estimates indicate that the threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) global mean warming. [WGI AR5 SPM, 5.8, 13.4, 13.5] Abrupt and irreversible ice loss from a potential instability of marine-based areas of the Antarctic ice sheet in response to climate forcing is possible, but current evidence and understanding is insufficient to make a quantitative assessment. [19.6; WGI AR5 SPM, 5.8, 13.4, 13.5] Sea level rise of 0.45 to 0.82 m (mean 0.63 m) is *likely* by 2081–2100 under RCP8.5 (*medium confidence*) [WGI AR5 Tables SPM.2 and 13.5], with sea level continuing to rise beyond 2100.

The Atlantic Meridional Overturning Circulation (AMOC) will *very likely* weaken over the 21st century, with a best estimate of 34% loss (range 12 to 54%) under RCP8.5. [WGI AR5 SPM, 12.4] The release of carbon dioxide (CO_2) or methane (CH_4) to the atmosphere from thawing permafrost carbon stocks over the 21st century is assessed to be in the range of 50 to 250 GtC for Representative Concentration Pathway 8.5 (RCP8.5) (*low confidence*). [WGI AR5 SPM, 6.4] A nearly ice-free Arctic Ocean in September before mid-century is *likely* under RCP8.5 (*medium confidence*). [WGI AR5 SPM, 11.3, 12.4, 12.5]

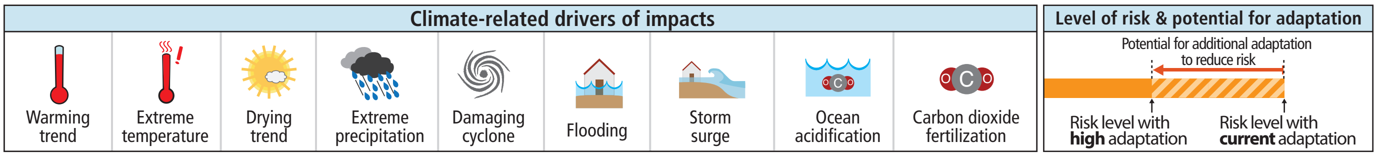
By 2100 for the high-emission scenario RCP8.5, the combination of high temperature and humidity in some areas for parts of the year is projected to compromise normal human activities, including growing food or working outdoors (*high confidence*). [11.8] Global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (*high confidence*). [7.4, 7.5, Table 7-3, Figures 7-1, 7-4, and 7-7, Box 7-1]

Under 4°C warming, some models project large increases in fire risk in parts of the world. [4.3, Figure 4-6] 4°C warming implies a substantial increase in extinction risk for terrestrial and freshwater species, although there is *low agreement* concerning the fraction of species at risk. [4.3] Widespread coral reef mortality is expected with significant impacts on coral reef ecosystems (*high confidence*). [5.4, Box CC-CR] Assessments of potential ecological impacts at and above 4°C warming imply a high risk of extensive loss of biodiversity with concomitant loss of ecosystem services (*high confidence*). [4.3, 19.3, 19.5, Box 25-6]

Projected large increases in exposure to water stress, fluvial and coastal flooding, negative impacts on crop yields, and disruption of ecosystem function and services would represent large, potentially compounding impacts of climate change on society generally and on the global economy. [19.4 to 19.6]

of the 21st century and beyond), climate change will amplify existing climate-related risks and create new risks for natural and human systems, dependent on the magnitude and rate of climate change and on the vulnerability and exposure of interlinked human and natural systems. Some of these risks will be limited to a particular sector or region, and others will have cascading effects. To a lesser extent, climate change will also have some potential benefits. A selection of key sectoral risks identified with *medium* to *high confidence* is presented in Table TS.4.

Table TS.4 | Key sectoral risks from climate change and the potential for reducing risks through adaptation and mitigation. Key risks have been identified based on assessment of the relevant scientific, technical, and socioeconomic literature detailed in supporting chapter sections. Identification of key risks was based on expert judgment using the following specific criteria: large magnitude, high probability, or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation. Each key risk is characterized as very low to very high for three timeframes: the present, near term (here, assessed over 2030–2040), and longer term (here, assessed over 2080–2100). The risk levels integrate probability and consequence over the widest possible range of potential outcomes, based on available literature. These potential outcomes result from the interaction of climate-related hazards, vulnerability, and exposure. Each risk level reflects total risk from climatic and non-climatic factors. For the near-term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially for different emission scenarios. For the longer-term era of climate options, risk levels are presented for two scenarios of global mean temperature increase (2°C and 4°C above preindustrial levels). These scenarios illustrate the potential for mitigation and adaptation to reduce the risks related to climate change. For the present, risk levels were estimated for current adaptation and a hypothetical highly adapted state, identifying where current adaptation deficits exist. For the two future timeframes, risk levels were estimated for a continuation of current adaptation and for a highly adapted state, representing the potential for and limits to adaptation. Climate-related drivers of impacts are indicated by icons. Risk levels are not necessarily comparable because the assessment considers potential impacts and adaptation in different physical, biological, and human systems across diverse contexts. This assessment of risks acknowledges the importance of differences in values and objectives in interpretation of the assessed risk levels.



Global Risks

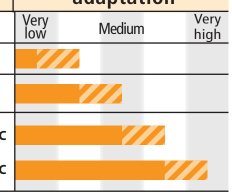
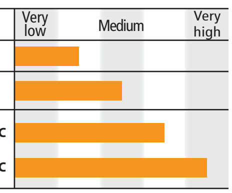
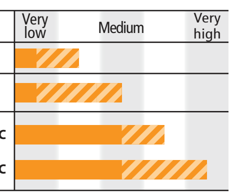
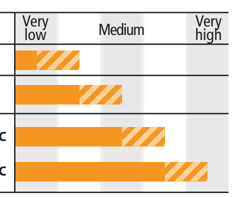
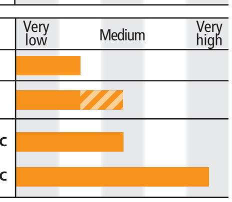
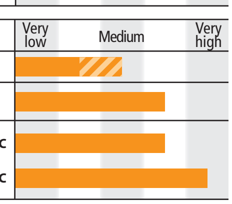
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Reduction in terrestrial carbon sink: Carbon stored in terrestrial ecosystems is vulnerable to loss back into the atmosphere, resulting from increased fire frequency due to climate change and the sensitivity of ecosystem respiration to rising temperatures (*medium confidence*) [4.2, 4.3]	• Adaptation options include managing land use (including deforestation), fire and other disturbances, and non-climatic stressors.	Warming trend, Extreme temperature, Drying trend	Present; Near term (2030–2040); Long term (2080–2100) 2°C / 4°C	
Boreal tipping point: Arctic ecosystems are vulnerable to abrupt change related to the thawing of permafrost, spread of shrubs in tundra, and increase in pests and fires in boreal forests (*medium confidence*) [4.3, Box 4-4]	• There are few adaptation options in the Arctic.	Warming trend, Extreme temperature	Present; Near term (2030–2040); Long term (2080–2100) 2°C / 4°C	
Amazon tipping point: Moist Amazon forests could change abruptly to less-carbon-dense, drought- and fire-adapted ecosystems (*low confidence*) [4.3, Box 4-3]	• Policy and market measures can reduce deforestation and fire.	Warming trend, Extreme temperature, Drying trend	Present; Near term (2030–2040); Long term (2080–2100) 2°C / 4°C	
Increased risk of species extinction: A large fraction of the species assessed is vulnerable to extinction due to climate change, often in interaction with other threats. Species with an intrinsically low dispersal rate, especially when occupying flat landscapes where the projected climate velocity is high, and species in isolated habitats such as mountaintops, islands, or small protected areas are especially at risk. Cascading effects through organism interactions, especially those vulnerable to phenological changes, amplify risk (*high confidence*) [4.3, 4.4]	• Adaptation options include reduction of habitat modification and fragmentation, pollution, over-exploitation, and invasive species; protected area expansion; assisted dispersal; and *ex situ* conservation.	Warming trend, Extreme temperature, Drying trend	Present; Near term (2030–2040); Long term (2080–2100) 2°C / 4°C	
Reduced growth and survival of commercially valuable shellfish and other calcifiers (e.g., reef-building corals, calcareous red algae) due to ocean acidification (*high confidence*) [5.3, 6.1, 6.3, 6.4, 30.3, Box CC-OA]	• Evidence for differential resistance and evolutionary adaptation of some species exists, but they are *likely* to be limited at higher CO_2 concentrations and temperatures. • Adaptation options include exploiting more resilient species or protecting habitats with low natural CO_2 levels, as well as reducing other stresses, mainly pollution, and limiting pressures from tourism and fishing.	Ocean acidification	Present; Near term (2030–2040); Long term (2080–2100) 2°C / 4°C	
Marine biodiversity loss with high rate of climate change (*medium confidence*) [6.3, 6.4, Table 30-4, Box CC-MB]	• Adaptation options are limited to reducing other stresses, mainly pollution, and limiting pressures from coastal human activities such as tourism and fishing.	Warming trend, Extreme temperature, Ocean acidification	Present; Near term (2030–2040); Long term (2080–2100) 2°C / 4°C	

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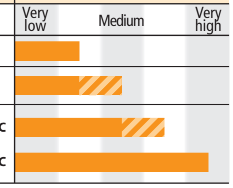
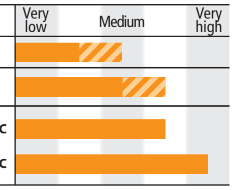
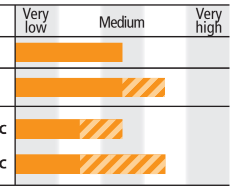
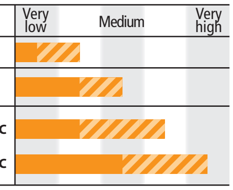
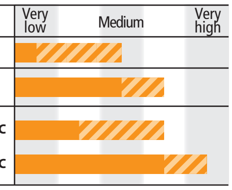
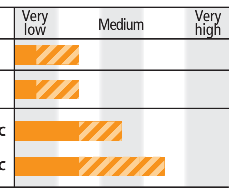
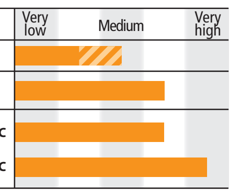
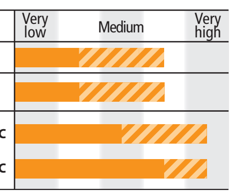
Table TS.4 (continued)

Global Risks				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Negative impacts on average crop yields and increases in yield variability due to climate change (*high confidence*) [7.2 to 7.5, Figure 7-5, Box 7-1]	• Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10%, and about 10% of projections showing yield losses of more than 25%, compared to the late 20th century. After 2050 the risk of more severe yield impacts increases and depends on the level of warming.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Urban risks associated with water supply systems (*high confidence*) [8.2, 8.3]	• Adaptation options include changes to network infrastructure as well as demand-side management to ensure sufficient water supplies and quality, increased capacities to manage reduced freshwater availability, and flood risk reduction.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Urban risks associated with energy systems (*high confidence*) [8.2, 8.4]	• Most urban centers are energy intensive, with energy-related climate policies focused only on mitigation measures. A few cities have adaptation initiatives underway for critical energy systems. There is potential for non-adapted, centralized energy systems to magnify impacts, leading to national and transboundary consequences from localized extreme events.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Urban risks associated with housing (*high confidence*) [8.3]	• Poor quality, inappropriately located housing is often most vulnerable to extreme events. Adaptation options include enforcement of building regulations and upgrading. Some city studies show the potential to adapt housing and promote mitigation, adaptation, and development goals simultaneously. Rapidly growing cities, or those rebuilding after a disaster, especially have opportunities to increase resilience, but this is rarely realized. Without adaptation, risks of economic losses from extreme events are substantial in cities with high-value infrastructure and housing assets, with broader economic effects possible.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Displacement associated with extreme events (*high confidence*) [12.4]	• Adaptation to extreme events is well understood, but poorly implemented even under present climate conditions. Displacement and involuntary migration are often temporary. With increasing climate risks, displacement is more likely to involve permanent migration.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Violent conflict arising from deterioration in resource-dependent livelihoods such as agriculture and pastoralism (*high confidence*) [12.5]	Adaptation options: • Buffering rural incomes against climate shocks, for example through livelihood diversification, income transfers, and social safety net provision • Early warning mechanisms to promote effective risk reduction • Well-established strategies for managing violent conflict that are effective but require significant resources, investment, and political will		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Declining work productivity, increasing morbidity (e.g., dehydration, heat stroke, and heat exhaustion), and mortality from exposure to heat waves. Particularly at risk are agricultural and construction workers as well as children, homeless people, the elderly, and women who have to walk long hours to collect water (*high confidence*) [13.2, Box 13-1]	• Adaptation options are limited for people who are dependent on agriculture and cannot afford agricultural machinery. • Adaptation options are limited in the construction sector where many poor people work under insecure arrangements. • Adaptation limits may be exceeded in certain areas in a +4°C world.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Reduced access to water for rural and urban poor people due to water scarcity and increasing competition for water (*high confidence*) [13.2, Box 13-1]	• Adaptation through reducing water use is not an option for the many people already lacking adequate access to safe water. Access to water is subject to various forms of discrimination, for instance due to gender and location. Poor and marginalized water users are unable to compete with water extraction by industries, large-scale agriculture, and other powerful users.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

For extended summary of sectoral risks and the more limited potential benefits, see introductory overviews for each sector below and also Chapters 3 to 13.

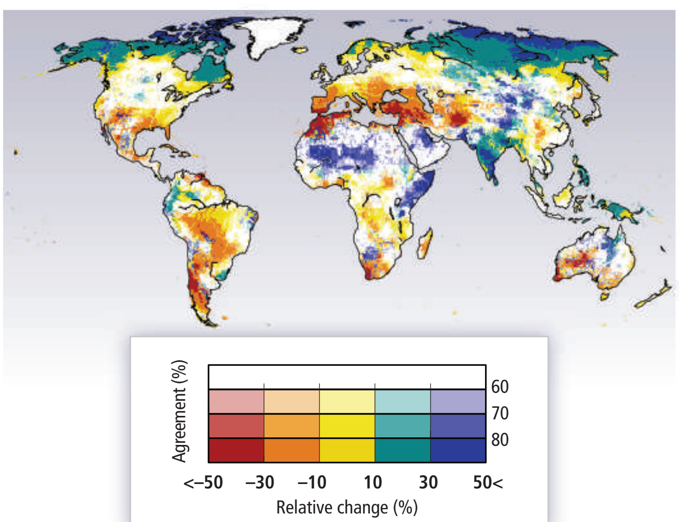
Freshwater Resources

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas concentrations (*robust evidence*, *high agreement*). The fraction of global population experiencing water scarcity and the fraction affected by major river floods increase with the level of warming in the 21st century. See, for example, Figure TS.6. [3.4, 3.5, 26.3, Table 3-2, Box 25-8]

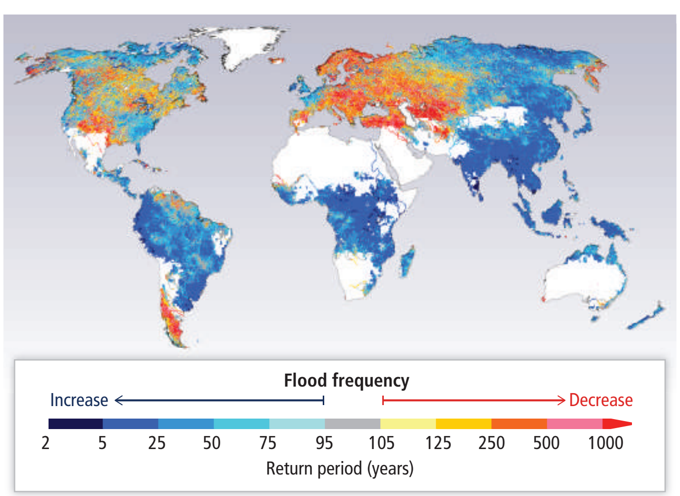
Climate change over the 21st century is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*robust evidence*, *high agreement*), intensifying competition for water among sectors (*limited evidence*, *medium agreement*). In presently dry regions, drought frequency will *likely* increase by the end of the 21st century under RCP8.5 (*medium confidence*). In contrast, water resources are projected to increase at high latitudes (*robust evidence*, *high agreement*). Climate change is projected to reduce raw water quality and pose risks to drinking water quality even with conventional treatment, due to interacting factors: increased temperature; increased sediment, nutrient, and pollutant loadings from heavy rainfall; increased concentration of pollutants during droughts; and disruption of treatment facilities during floods (*medium evidence*, *high agreement*). [3.2, 3.4, 3.5, 22.3, 23.9, 25.5, 26.3, Tables 3-2 and 23-3, Boxes CC-RF and CC-WE; WGI AR5 12.4]

Adaptive water management techniques, including scenario planning, learning-based approaches, and flexible and low-regret solutions, can help create resilience to uncertain hydrological changes and impacts due to climate change (*limited evidence*, *high agreement*). Barriers to progress include lack of human and institutional capacity, financial resources, awareness, and communication. [3.6, Box 25-2]

(A)



(B)



(C)

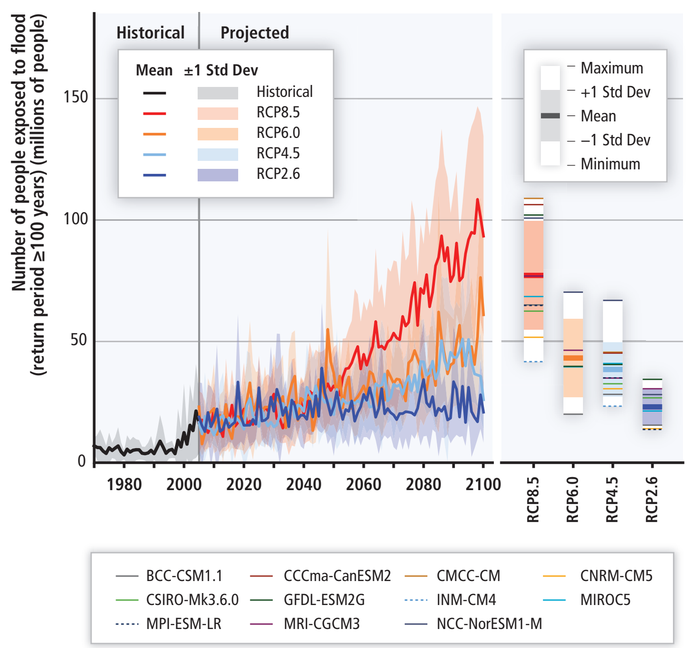


Figure TS.6 | (A) Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980–2010. Color hues show the multi-model mean change across 5 General Circulation Models (GCMs) and 11 Global Hydrological Models (GHMs), and saturation shows the agreement on the sign of change across all 55 GHM–GCM combinations (percentage of model runs agreeing on the sign of change). (B and C) Projected change in river flood return period and exposure, based on one hydrological model driven by 11 GCMs and on global population in 2005. (B) In the 2080s under RCP8.5, multi-model median return period (years) for the 20th-century 100-year flood. (C) Global exposure to the 20th-century 100-year flood in millions of people. Left: Ensemble means of historical (black line) and future simulations (colored lines) for each scenario. Shading denotes ±1 standard deviation. Right: Maximum and minimum (extent of white), mean (thick colored lines), ±1 standard deviation (extent of shading), and projections of each GCM (thin colored lines) averaged over the 21st century. [Figures 3-4 and 3-6]

Terrestrial and Freshwater Ecosystems

Climate change is projected to be a powerful stressor on terrestrial and freshwater ecosystems in the second half of the 21st century, especially under high-warming scenarios such as RCP6.0 and 8.5 (*high confidence*). Through to 2040 globally, direct human impacts such as land-use change, pollution, and water resource development will continue to dominate threats to most freshwater ecosystems (*high confidence*) and most terrestrial ecosystems (*medium confidence*). Many species will be unable to track suitable climates under mid- and high-range rates of climate change (i.e., RCP4.5, 6.0, and 8.5) during the 21st century (*medium confidence*). Lower rates of change (i.e., RCP2.6) will pose fewer problems. See Figure TS.7. Some species will adapt to new climates. Those that cannot adapt sufficiently fast will decrease in abundance or go extinct in part or all of their ranges. Increased tree mortality and associated forest dieback is projected to occur in many regions over the 21st century, due to increased temperatures and drought (*medium confidence*). Forest dieback poses risks for carbon storage, biodiversity, wood production, water quality, amenity, and economic activity. Management actions, such as maintenance of genetic diversity, assisted species migration and dispersal, manipulation of disturbance regimes (e.g., fires, floods), and reduction of other stressors, can reduce, but not eliminate, risks of impacts to terrestrial and freshwater ecosystems due to climate change, as well as increase the inherent capacity of ecosystems and their species to adapt to a changing climate (*high confidence*). [4.3, 4.4, 25.6, 26.4, Boxes 4-2, 4-3, and CC-RF]

A large fraction of both terrestrial and freshwater species faces increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other stressors, such as habitat modification, over-exploitation, pollution, and invasive species (*high confidence*). Extinction risk is increased under all RCP scenarios, with risk increasing with both magnitude and rate of climate change. Models project that the risk of species extinctions will increase in the future due to climate change, but there is *low agreement* concerning the fraction of species at increased risk, the regional and taxonomic distribution of such extinctions, and the timeframe over which extinctions could occur. Some aspects leading to uncertainty in the quantitative projections of extinction risks were not taken into account in previous models; as more realistic details are included, it has been shown that the extinction risks may be either under- or overestimated when based on simpler models. [4.3, 25.6]

Within this century, magnitudes and rates of climate change associated with medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5) pose high risk of abrupt and irreversible regional-scale change in the composition, structure, and function of

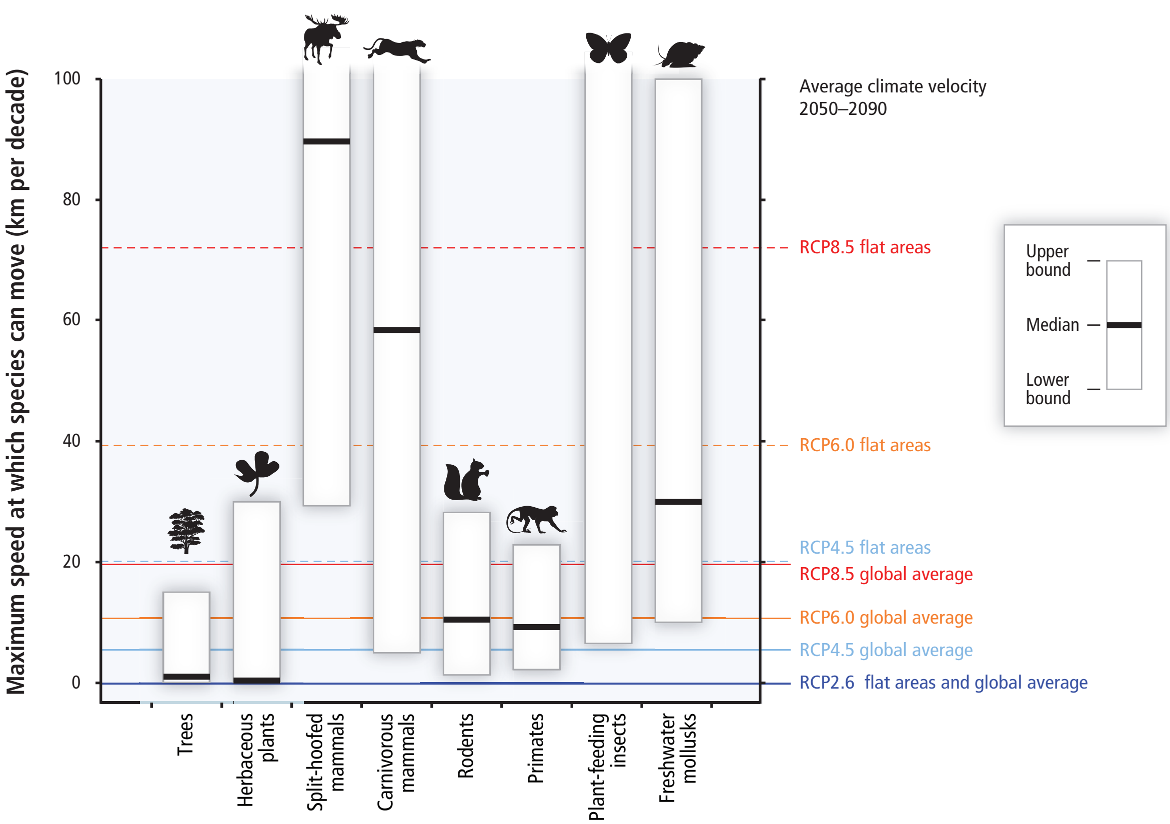


Figure TS.7 | Maximum speeds at which species can move across landscapes (based on observations and models; vertical axis on left), compared with speeds at which temperatures are projected to move across landscapes (climate velocities for temperature; vertical axis on right). Human interventions, such as transport or habitat fragmentation, can greatly increase or decrease speeds of movement. White boxes with black bars indicate ranges and medians of maximum movement speeds for trees, plants, mammals, plant-feeding insects (median not estimated), and freshwater mollusks. For RCP2.6, 4.5, 6.0, and 8.5 for 2050–2090, horizontal lines show climate velocity for the global-land-area average and for large flat regions. Species with maximum speeds below each line are expected to be unable to track warming in the absence of human intervention. [Figure 4-5]

terrestrial and freshwater ecosystems, including wetlands (*medium confidence*). Examples that could lead to substantial impact on climate are the boreal–tundra Arctic system (*medium confidence*) and the Amazon forest (*low confidence*). For the boreal–tundra system, continued climate change will transform the species composition, land cover, drainage, and permafrost extent of the boreal–tundra system, leading to decreased albedo and the release of greenhouse gases (*medium confidence*), with adaptation measures unable to prevent substantial change (*high confidence*). Increased severe drought together with land-use change and forest fire would cause much of the Amazon forest to transform to less-dense drought- and fire-adapted ecosystems, increasing risk for biodiversity while decreasing net carbon uptake from the atmosphere (*low confidence*). Large reductions in deforestation, as well as wider application of effective wildfire management, will lower the risk of abrupt change in the Amazon, as well as potential negative impacts of that change (*medium confidence*). [4.2, 4.3, Figure 4-8, Boxes 4-3 and 4-4]

The natural carbon sink provided by terrestrial ecosystems is partially offset at the decadal timescale by carbon released through the conversion of natural ecosystems (principally forests) to farm and grazing land and through ecosystem degradation (*high confidence*). Carbon stored in the terrestrial biosphere (e.g., in peatlands, permafrost, and forests) is susceptible to loss to the atmosphere as a result of climate change, deforestation, and ecosystem degradation. [4.2, 4.3, Box 4-3]

Coastal Systems and Low-lying Areas

Due to sea level rise projected throughout the 21st century and beyond, coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion (*very high confidence*). The population and assets projected to be exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, and urbanization (*high confidence*). The relative costs of coastal adaptation vary strongly among and within regions and countries for the 21st century. Some low-lying developing countries and small island states are expected to face very high impacts that, in some cases, could have associated damage and adaptation costs of several percentage points of GDP. [5.3 to 5.5, 8.2, 22.3, 24.4, 25.6, 26.3, 26.8, Table 26-1, Box 25-1]

Marine Systems

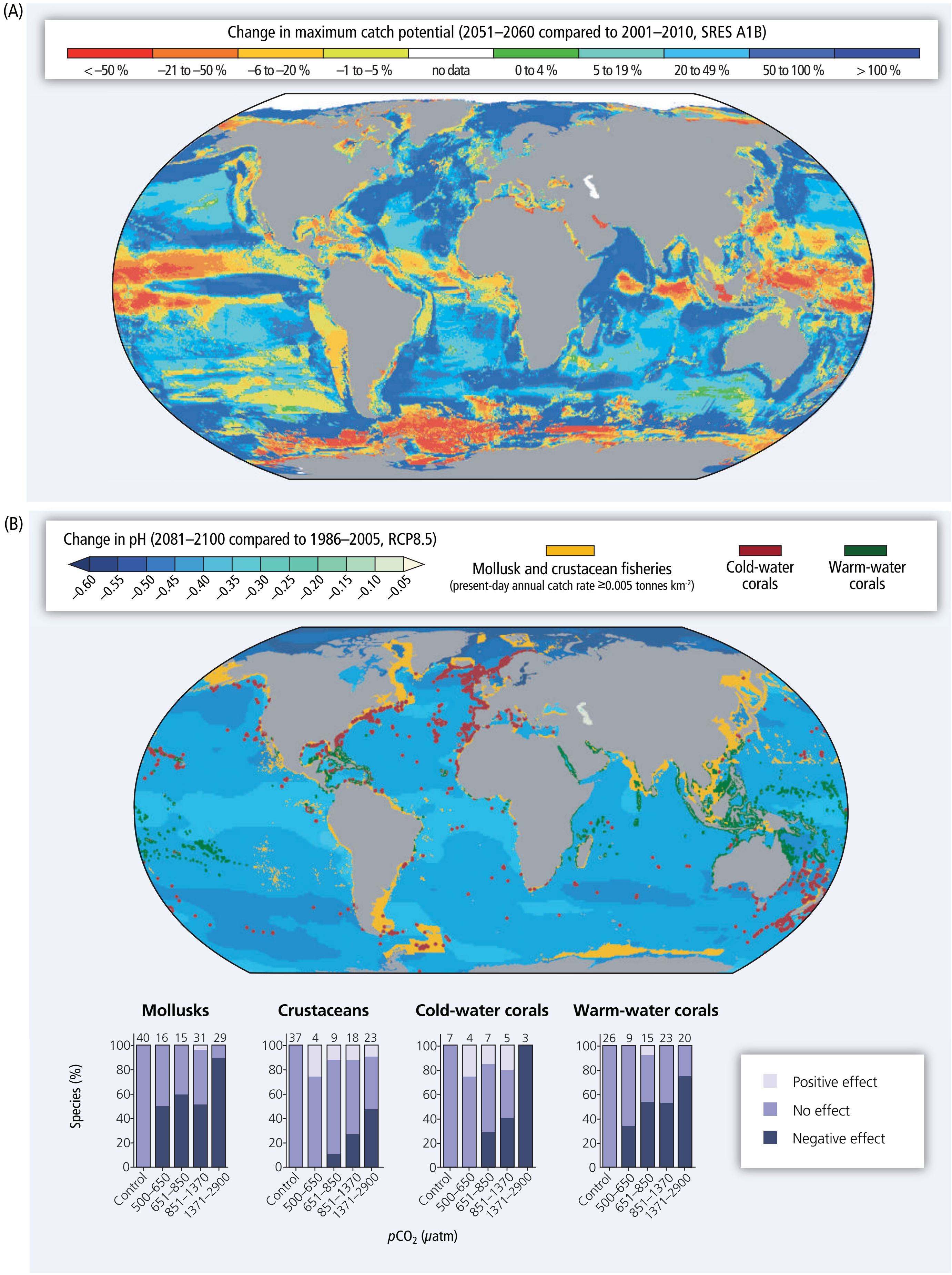
By mid 21st century, spatial shifts of marine species will cause species richness and fisheries catch potential to increase, on average, at mid and high latitudes (*high confidence*) and to decrease at tropical latitudes (*medium confidence*), resulting in global redistribution of catch potential for fishes and invertebrates, with implications for food security (*medium confidence*). Spatial shifts of marine species due to projected warming will cause high-latitude invasions and high local-extinction rates in the tropics and semi-enclosed seas (*medium confidence*). Animal displacements will cause a 30 to 70% increase in the fisheries yield of some high-latitude regions by 2055 (relative to 2005), a redistribution at mid latitudes, and a drop of 40 to 60% in some of the tropics and the Antarctic, for 2°C warming above preindustrial levels (*medium confidence* for direction of fisheries' yield trends, *low confidence* for the precise magnitudes of yield change). See Figure TS.8A. The progressive expansion of oxygen minimum zones and anoxic "dead zones" is projected to further constrain the habitat of fishes and other O_2-dependent organisms (*medium confidence*). Open-ocean net primary production is projected to redistribute and, by 2100, fall globally under all RCP scenarios. [6.3 to 6.5, 7.4, 25.6, 28.3, 30.4 to 30.6, Boxes CC-MB and CC-PP]

Due to projected climate change by the mid 21st century and beyond, global marine-species redistribution and marine-biodiversity reduction in sensitive regions will challenge the sustained provision of fisheries productivity and other ecosystem goods and services (*high confidence*). Socioeconomic vulnerability is highest in developing tropical countries, leading to risks from reduced supplies, income, and employment from marine fisheries. [6.4, 6.5]

For medium- to high-emission scenarios (RCP4.5, 6.0, and 8.5), ocean acidification poses substantial risks to marine ecosystems, especially polar ecosystems and coral reefs, associated with impacts on the physiology, behavior, and population dynamics of individual species from phytoplankton to animals (*medium* to *high confidence*). See Box TS.7. Highly calcified mollusks, echinoderms, and reef-building corals are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*), with potentially detrimental consequences for fisheries and livelihoods (Figure TS.8B). Ocean acidification acts together with other global changes (e.g., warming, decreasing oxygen levels) and with local changes (e.g., pollution, eutrophication) (*high confidence*). Simultaneous drivers, such as warming and ocean acidification, can lead to interactive, complex, and amplified impacts for species and ecosystems. [5.4, 6.3 to 6.5, 22.3, 25.6, 28.3, 30.5, Boxes CC-CR and CC-OA]

Climate change adds to the threats of over-fishing and other non-climatic stressors, thus complicating marine management regimes (*high confidence*). In the short term, strategies including climate forecasting and early warning systems can reduce risks from ocean warming and acidification for some fisheries and aquaculture industries. Fisheries and aquaculture industries with high-technology

Figure TS.8 | Climate change risks for fisheries. (A) Projected global redistribution of maximum catch potential of ~1000 exploited fish and invertebrate species. Projections compare the 10-year averages 2001–2010 and 2051–2060 using SRES A1B, without analysis of potential impacts of overfishing or ocean acidification. (B) Marine mollusk and crustacean fisheries (present-day estimated annual catch rates ≥0.005 tonnes km^{-2}) and known locations of cold- and warm-water corals, depicted on a global map showing the projected distribution of ocean acidification under RCP8.5 (pH change from 1986–2005 to 2081–2100). [WGI AR5 Figure SPM.8] The bottom panel compares sensitivity to ocean acidification across mollusks, crustaceans, and corals, vulnerable animal phyla with socioeconomic relevance (e.g., for coastal protection and fisheries). The number of species analyzed across studies is given for each category of elevated CO_2. For 2100, RCP scenarios falling within each CO_2 partial pressure (pCO_2) category are as follows: RCP4.5 for 500–650 μatm (approximately equivalent to ppm in the atmosphere), RCP6.0 for 651–850 μatm, and RCP8.5 for 851–1370 μatm. By 2150, RCP8.5 falls within the 1371–2900 μatm category. The control category corresponds to 380 μatm. [6.1, 6.3, 30.5, Figures 6-10 and 6-14; WGI AR5 Box SPM.1]


(A)
Change in maximum catch potential (2051–2060 compared to 2001–2010, SRES A1B)
< –50 %
–21 to –50 %
–6 to –20 %
–1 to –5 %
no data
0 to 4 %
5 to 19 %
20 to 49 %
50 to 100 %
> 100 %
(B)
Change in pH (2081–2100 compared to 1986–2005, RCP8.5)
–0.60 –0.55 –0.50 –0.45 –0.40 –0.35 –0.30 –0.25 –0.20 –0.15 –0.10 –0.05
Mollusk and crustacean fisheries
(present-day annual catch rate ≥0.005 tonnes km-2)
Cold-water corals
Warm-water corals
Mollusks
40 16 15 31 29
Crustaceans
37 4 9 18 23
Cold-water corals
7 4 7 5 3
Warm-water corals
26 9 15 23 20
Species (%)
0 20 40 60 80 100
Control
500–650
651–850
851–1370
1371–2900
pCO2 (μatm)
Positive effect
No effect
Negative effect

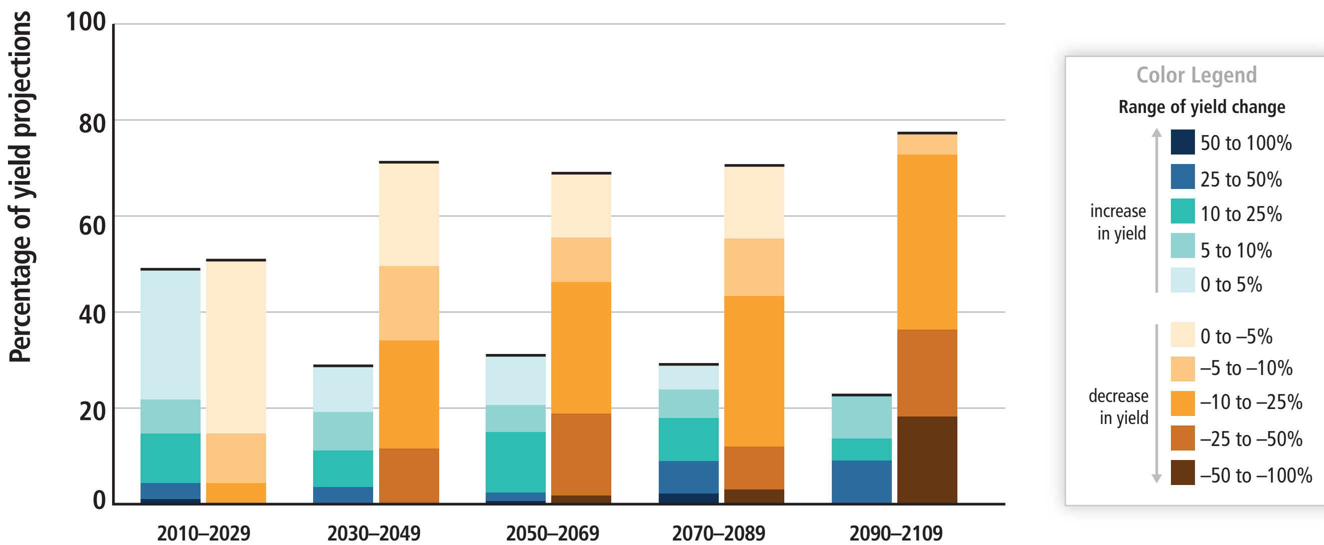


Figure TS.9 | Summary of projected changes in crop yields, due to climate change over the 21st century. The figure includes projections for different emission scenarios, for tropical and temperate regions, and for adaptation and no-adaptation cases combined. Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. For five timeframes in the near term and long term, data (n=1090) are plotted in the 20-year period on the horizontal axis that includes the midpoint of each future projection period. Changes in crop yields are relative to late-20th-century levels. Data for each timeframe sum to 100%. [Figure 7-5]

and/or large investments, as well as marine shipping and oil and gas industries, have high capacities for adaptation due to greater development of environmental monitoring, modeling, and resource assessments. For smaller-scale fisheries and developing countries, building social resilience, alternative livelihoods, and occupational flexibility represent important strategies for reducing the vulnerability of ocean-dependent human communities. [6.4, 7.3, 7.4, 25.6, 29.4, 30.6, 30.7]

Food Security and Food Production Systems

For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation is projected to negatively impact aggregate production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (*medium confidence*). Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10%, and about 10% of projections showing yield losses of more than 25%, compared to the late 20th century. After 2050 the risk of more severe yield impacts increases and depends on the level of warming. See Figure TS.9. Climate change is projected to progressively increase inter-annual variability of crop yields in many regions. These projected impacts will occur in the context of rapidly rising crop demand. [7.4, 7.5, 22.3, 24.4, 25.7, 26.5, Table 7-2, Figures 7-4, 7-5, 7-6, 7-7, and 7-8]

All aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (*high confidence*). Redistribution of marine fisheries catch potential towards higher latitudes poses risk of reduced supplies, income, and employment in tropical countries, with potential implications for food security (*medium confidence*). Global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (*high confidence*). Risks to food security are generally greater in low-latitude areas. [6.3 to 6.5, 7.4, 7.5, 9.3, 22.3, 24.4, 25.7, 26.5, Table 7-3, Figures 7-1, 7-4, and 7-7, Box 7-1]

Urban Areas

Many global risks of climate change are concentrated in urban areas (*medium confidence*). Steps that build resilience and enable sustainable development can accelerate successful climate-change adaptation globally. Heat stress, extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, and water scarcity pose risks in urban areas for people, assets, economies, and ecosystems (*very high confidence*). Risks are amplified for those lacking essential infrastructure and services or living in poor-quality housing and exposed areas. Reducing basic service deficits, improving housing, and building resilient infrastructure systems could significantly reduce vulnerability and exposure in urban areas. Urban adaptation benefits from effective multi-level urban risk governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector, and appropriate financing and institutional development (*medium confidence*). Increased capacity, voice, and influence of low-income groups and vulnerable communities and their partnerships with local governments also benefit adaptation. [3.5, 8.2 to 8.4, 22.3, 24.4, 24.5, 26.8, Table 8-2, Boxes 25-9 and CC-HS]

Rural Areas

Major future rural impacts are expected in the near term and beyond through impacts on water availability and supply, food security, and agricultural incomes, including shifts in production areas of food and non-food crops across the world (*high*

***confidence*)**. These impacts are expected to disproportionately affect the welfare of the poor in rural areas, such as female-headed households and those with limited access to land, modern agricultural inputs, infrastructure, and education. Climate change will increase international agricultural trade volumes in both physical and value terms (*limited evidence*, *medium agreement*). Importing food can help countries adjust to climate change-induced domestic productivity shocks while short-term food deficits in developing countries with low income may have to be met through food aid. Further adaptations for agriculture, water, forestry, and biodiversity can occur through policies taking account of rural decision-making contexts. Trade reform and investment can improve market access for small-scale farms (*medium confidence*). Valuation of non-marketed ecosystem services and limitations of economic valuation models that aggregate across contexts pose challenges for valuing rural impacts. [9.3, 25.9, 26.8, 28.2, 28.4, Box 25-5]

Key Economic Sectors and Services

For most economic sectors, the impacts of drivers such as changes in population, age structure, income, technology, relative prices, lifestyle, regulation, and governance are projected to be large relative to the impacts of climate change (*medium evidence*, *high agreement*). Climate change is projected to reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*robust evidence*, *high agreement*). Climate change is projected to affect energy sources and technologies differently, depending on resources (e.g., water flow, wind, insolation), technological processes (e.g., cooling), or locations (e.g., coastal regions, floodplains) involved. More severe and/or frequent extreme weather events and/or hazard types are projected to increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in developing countries. Large-scale public-private risk reduction initiatives and economic diversification are examples of adaptation actions. [3.5, 10.2, 10.7, 10.10, 17.4, 17.5, 25.7, 26.7 to 26.9, Box 25-7]

Climate change may influence the integrity and reliability of pipelines and electricity grids (*medium evidence*, *medium agreement*). Climate change may require changes in design standards for the construction and operation of pipelines and of power transmission and distribution lines. Adopting existing technology from other geographical and climatic conditions may reduce the cost of adapting new infrastructure as well as the cost of retrofitting existing pipelines and grids. Climate change may negatively affect transport infrastructure (*limited evidence*, *high agreement*). All infrastructure is vulnerable to freeze-thaw cycles; paved roads are particularly vulnerable to temperature extremes, unpaved roads and bridges to precipitation extremes. Transport infrastructure on ice or permafrost is especially vulnerable. [10.2, 10.4, 25.7, 26.7]

Climate change will affect tourism resorts, particularly ski resorts, beach resorts, and nature resorts (*robust evidence*, *high agreement*), and tourists may spend their holidays at higher altitudes and latitudes (*medium evidence*, *high agreement*). The economic implications of climate-change-induced changes in tourism demand and supply entail gains for countries closer to the poles and countries with higher elevations and losses for other countries. [10.6, 25.7]

Global economic impacts from climate change are difficult to estimate. Economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors. With these recognized limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income (±1 standard deviation around the mean) (*medium evidence*, *medium agreement*). Losses are *more likely than not* to be greater, rather than smaller, than this range (*limited evidence*, *high agreement*). Additionally, there are large differences between and within countries. Losses accelerate with greater warming (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. Estimates of the incremental economic impact of emitting carbon dioxide lie between a few dollars and several hundreds of dollars per tonne of carbon[3] (*robust evidence*, *medium agreement*). Estimates vary strongly with the assumed damage function and discount rate. [10.9]

Human Health

Until mid-century, projected climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*). Throughout the 21st century, climate change is expected to lead to increases in ill-health in many regions and especially in developing countries with low income, as compared to a baseline without climate change (*high confidence*). Examples include greater likelihood of injury, disease, and death due to more intense heat waves and fires (*very high confidence*); increased likelihood of under-nutrition resulting from diminished food production in poor regions (*high confidence*); risks from lost work capacity and reduced labor productivity in vulnerable populations; and increased risks from food- and water-borne diseases (*very high confidence*) and vector-borne diseases (*medium confidence*). Impacts on health will be reduced, but not eliminated, in populations that benefit from rapid social and economic development, particularly among the poorest and least healthy groups (*high confidence*). Climate change will increase demands for health care services and facilities, including public health programs, disease prevention activities, health care personnel, infrastructure, and supplies for treatment (*medium evidence*, *high agreement*). Positive effects are expected to include modest reductions in cold-related mortality and morbidity in some areas due to fewer cold extremes (*low confidence*), geographical shifts in food production (*medium confidence*), and reduced capacity of vectors to transmit some diseases. But globally over the 21st century, the magnitude and severity of negative impacts are projected to increasingly outweigh positive impacts (*high confidence*). The most effective vulnerability reduction measures for health in the near term are programs that implement and improve basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services,

[3] 1 tonne of carbon = 3.667 tonne of CO_2

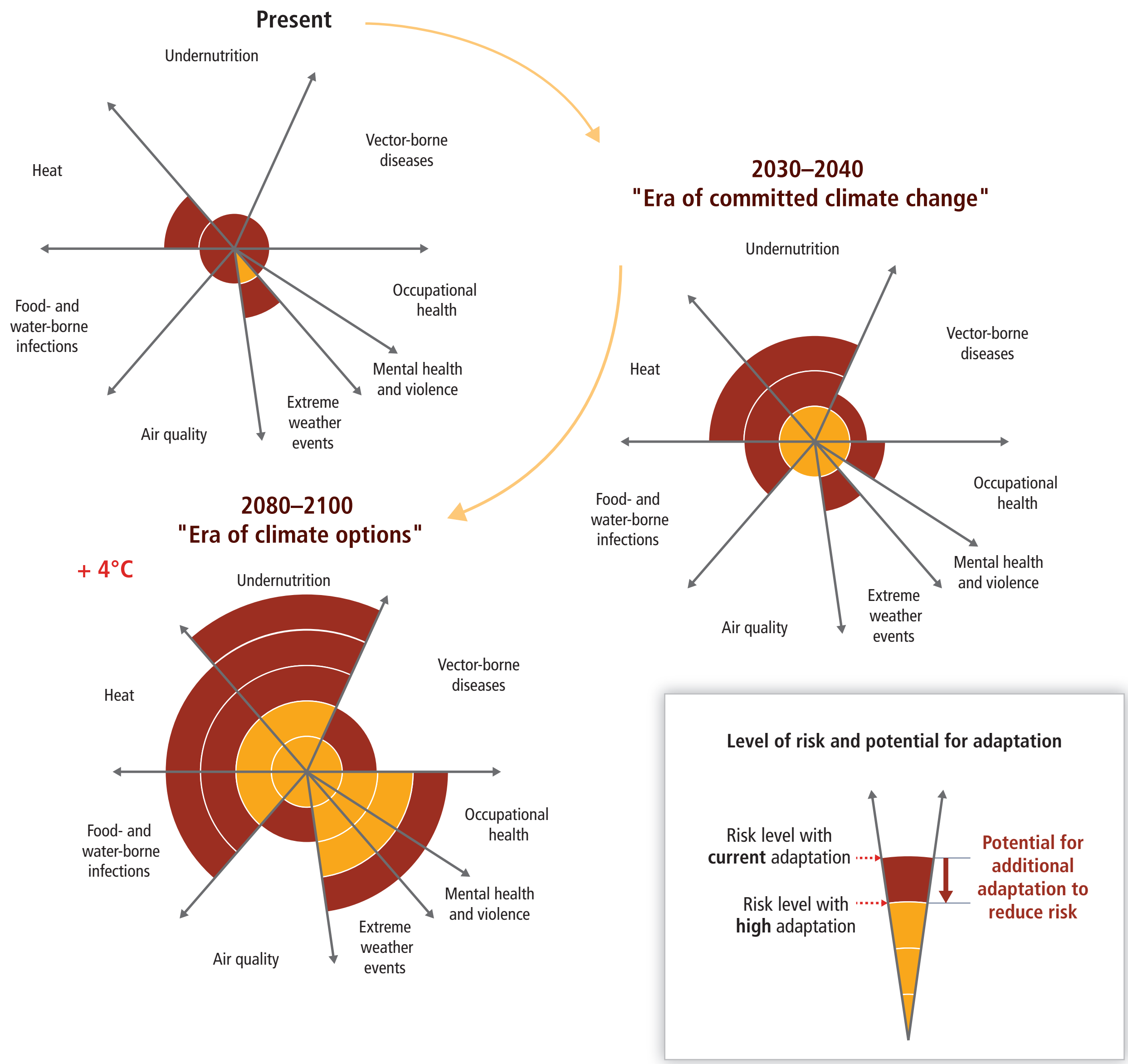


Figure TS.10 | Conceptual presentation of health risks from climate change and the potential for risk reduction through adaptation. Risks are identified in eight health-related categories based on assessment of the literature and expert judgments by authors of Chapter 11. The width of the slices indicates in a qualitative way relative importance in terms of burden of ill-health globally at present. Risk levels are assessed for the present and for the near-term era of committed climate change (here, for 2030–2040). For some categories, for example, vector-borne diseases, heat/cold stress, and agricultural production and undernutrition, there may be benefits to health in some areas, but the net impact is expected to be negative. Risk levels are also presented for the longer-term era of climate options (here, for 2080–2100) for global mean temperature increase of 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state, indicated by different colors. [Figure 11-6]

increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*). By 2100 for the high-emission scenario RCP8.5, the combination of high temperature and humidity in some areas for parts of the year is projected to compromise normal human activities, including growing food or working outdoors (*high confidence*). See Figure TS.10. [8.2, 11.3 to 11.8, 19.3, 22.3, 25.8, 26.6, Figure 25-5, Box CC-HS]

Human Security

Human security will be progressively threatened as the climate changes (*robust evidence*, *high agreement*). Human insecurity almost never has single causes, but instead emerges from the interaction of multiple factors. Climate change is an important factor in threats to human security through (1) undermining livelihoods, (2) compromising culture and identity, (3) increasing migration that people would rather have avoided, and (4) challenging the ability of states to provide the conditions necessary for human security. See Figure TS.11. [12.1 to 12.4, 12.6]

Climate change will compromise the cultural values that are important for community and individual well-being (*medium evidence*, *high agreement*). The effect of climate change on culture will vary across societies and over time, depending on cultural resilience and the mechanisms for maintaining and transferring knowledge. Changing weather and climatic conditions threaten cultural practices

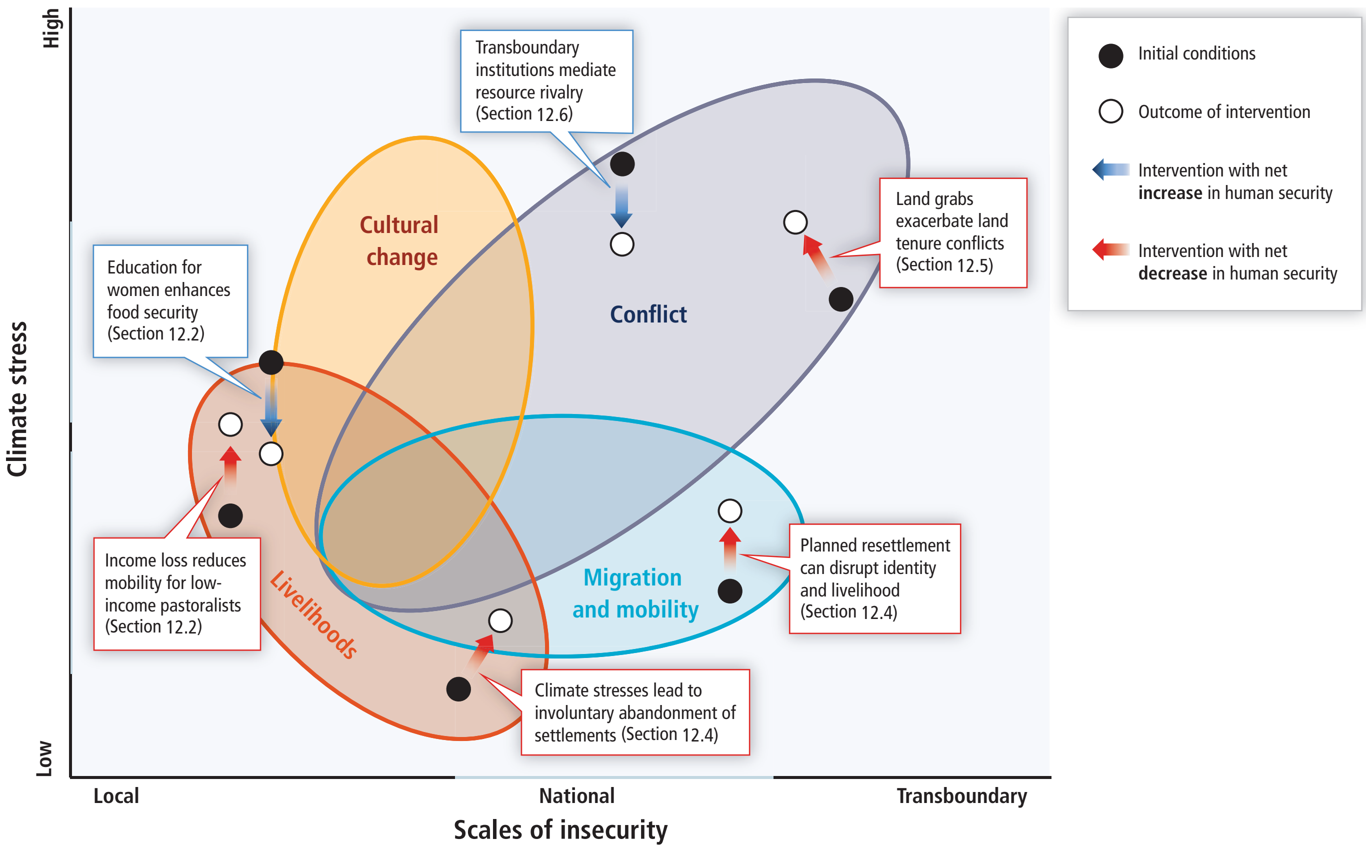


Figure TS.11 | Schematic of climate change risks for human security and the interactions between livelihoods, conflict, culture, and migration. Interventions and policies are indicated by the difference between initial conditions (solid black circles) and the outcome of intervention (white circles). Some interventions (blue arrows) show net increase in human security while others (red arrows) lead to net decrease in human security. [Figure 12-3]

embedded in livelihoods and expressed in narratives, worldviews, identity, community cohesion, and sense of place. Loss of land and displacement, for example, on small islands and coastal communities, have well documented negative cultural and well-being impacts. [12.3, 12.4]

Climate change over the 21st century is projected to increase displacement of people (*medium evidence*, *high agreement*). Displacement risk increases when populations that lack the resources for planned migration experience higher exposure to extreme weather events, in both rural and urban areas, particularly in developing countries with low income. Expanding opportunities for mobility can reduce vulnerability for such populations. Changes in migration patterns can be responses to both extreme weather events and longer-term climate variability and change, and migration can also be an effective adaptation strategy. There is *low confidence* in quantitative projections of changes in mobility, due to its complex, multi-causal nature. [9.3, 12.4, 19.4, 22.3, 25.9]

Climate change can indirectly increase risks of violent conflicts in the form of civil war and inter-group violence by amplifying well-documented drivers of these conflicts such as poverty and economic shocks (*medium confidence*). Multiple lines of evidence relate climate variability to these forms of conflict. [12.5, 13.2, 19.4]

The impacts of climate change on the critical infrastructure and territorial integrity of many states are expected to influence national security policies (*medium evidence*, *medium agreement*). For example, land inundation due to sea level rise poses risks to the territorial integrity of small island states and states with extensive coastlines. Some transboundary impacts of climate change, such as changes in sea ice, shared water resources, and pelagic fish stocks, have the potential to increase rivalry among states, but robust national and intergovernmental institutions can enhance cooperation and manage many of these rivalries. [12.5, 12.6, 23.9, 25.9]

Livelihoods and Poverty

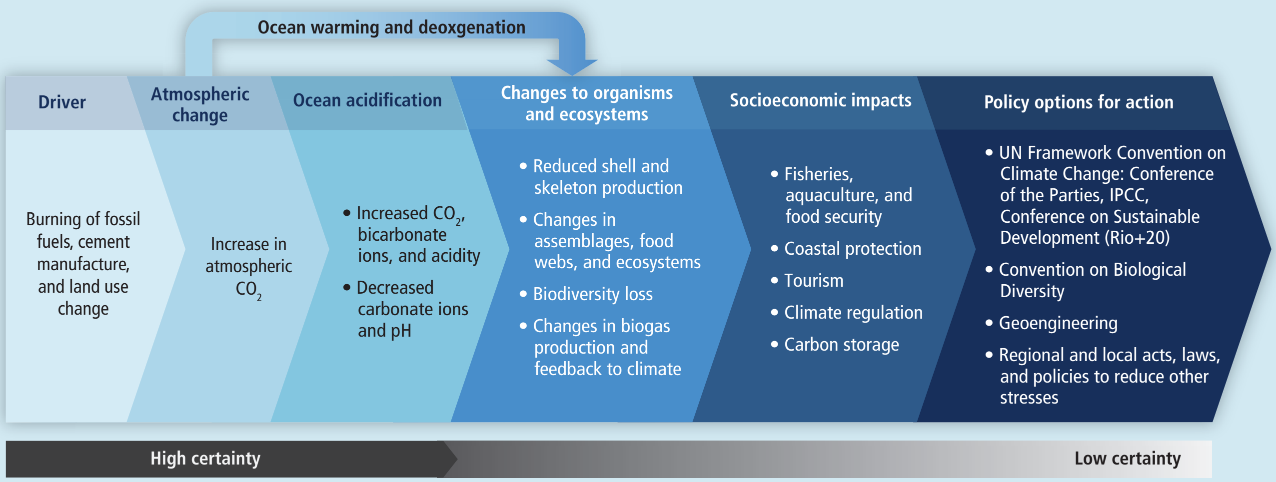
Throughout the 21st century, climate-change impacts are projected to slow down economic growth, make poverty reduction more difficult, further erode food security, and prolong existing and create new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*). Climate-change impacts are expected to exacerbate poverty in most developing countries and create new poverty pockets in countries with increasing inequality, in both developed and developing countries. In urban and rural areas, wage-labor-dependent poor households that are net buyers of food are expected to be particularly affected due to food price increases, including in regions with high food insecurity and high inequality (particularly in Africa), although the agricultural self-employed could benefit. Insurance programs, social protection measures, and disaster risk management may enhance long-term livelihood resilience

Box TS.7 | Ocean Acidification

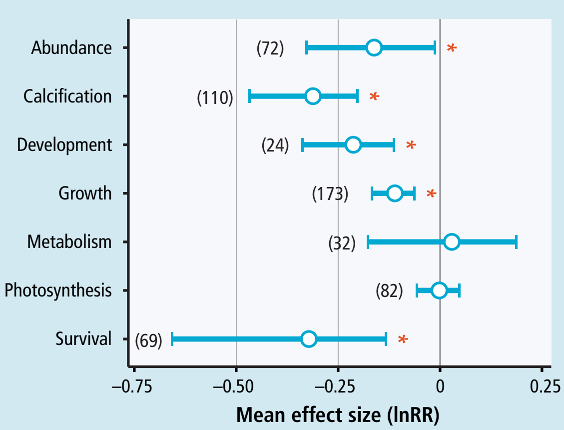
Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Box TS.7 Figure 1A). [WGI AR5 2.2] Eutrophication, upwelling, and deposition of atmospheric nitrogen and sulfur contribute to ocean acidification locally. [5.3, 6.1, 30.3] The fundamental chemistry of ocean acidification is well understood (*robust evidence*, *high agreement*). [30.3; WGI AR5 3.8, 6.4] It has been more difficult to understand and project changes within the more complex coastal systems. [5.3, 30.3]

Ocean acidification acts together with other global changes (e.g., warming, decreasing oxygen levels) and with local changes (e.g., pollution, eutrophication) (*high confidence*). Simultaneous drivers, such as warming and ocean acidification, can lead to interactive, complex, and amplified impacts for species and ecosystems. A pattern of positive and negative impacts of ocean acidification emerges for processes and organisms (*high confidence*; Box TS.7 Figure 1B), but key uncertainties remain from organismal to ecosystem levels. A wide range of sensitivities exists within and across organisms, with higher sensitivity in early life stages. [6.3] Lower pH decreases the rate of calcification of most, but not all, sea floor calcifiers, reducing their competitiveness with non-calcifiers (*robust evidence*, *medium agreement*). [5.4, 6.3] Ocean acidification stimulates dissolution of calcium carbonate (*very high confidence*). Growth and primary production are stimulated in seagrasses and some phytoplankton (*high confidence*), and harmful algal blooms could become more frequent (*limited evidence*, *medium agreement*). Serious behavioral disturbances have been reported in fishes

(A)



(B)



Box TS.7 Figure 1 | (A) Overview of the chemical, biological, and socioeconomic impacts of ocean acidification and of policy options. (B) Effect of near-future acidification (seawater pH reduction of ≤0.5 units) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival, which is not weighted. The log-transformed response ratio (lnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification, but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. The * denotes a statistically significant effect. [Figure OA-1, Box CC-OA]

Continued next page →

Box TS.7 (continued)

(*high confidence*). [6.3] Natural analogs at CO_2 vents indicate decreased species diversity, biomass, and trophic complexity. Shifts in organisms' performance and distribution will change both predator-prey and competitive interactions, which could impact food webs and higher trophic levels (*limited evidence*, *high agreement*). [6.3]

A few studies provide *limited evidence* for adaptation in phytoplankton and mollusks. However, mass extinctions in Earth history occurred during much slower rates of change in ocean acidification, combined with other drivers, suggesting that evolutionary rates may be too slow for sensitive and long-lived species to adapt to the projected rates of future change (*medium confidence*). [6.1]

The biological, ecological, and biogeochemical changes driven by ocean acidification will affect key ecosystem services. The oceans will become less efficient at absorbing CO_2 and hence moderating climate (*very high confidence*). [WGI AR5 Figure 6.26] The impacts of ocean acidification on coral reefs, together with those of thermal stress (driving mass coral bleaching and mortality) and sea level rise, will diminish their role in shoreline protection as well as their direct and indirect benefits to fishing and tourism industries (*limited evidence*, *high agreement*). [Box CC-CR] The global cost of production loss of mollusks could be over US$100 billion by 2100 (*low confidence*). The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and complex additive, antagonistic, and/or synergistic interactions will occur with disruptive ramifications for ecosystems as well as for important ecosystem goods and services.

among poor and marginalized people, if policies address poverty and multidimensional inequalities. [8.1, 8.3, 8.4, 9.3, 10.9, 13.2 to 13.4, 22.3, 26.8]

B-3. Regional Risks and Potential for Adaptation

Risks will vary through time across regions and populations, dependent on myriad factors including the extent of adaptation and mitigation. A selection of key regional risks identified with *medium* to *high confidence* is presented in Table TS.5. Projected changes in climate and increasing atmospheric CO_2 will have positive effects for some sectors in some locations. For extended summary of regional risks and the more limited potential benefits, see introductory overviews for each region below and also WGII AR5 Part B: Regional Aspects, Chapters 21 to 30.

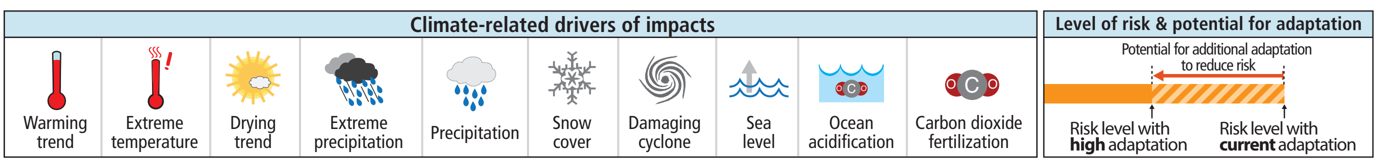
***Africa*. Climate change will amplify existing stress on water availability and on agricultural systems particularly in semi-arid environments (*high confidence*).** Increasing temperatures and changes in precipitation are *very likely* to reduce cereal crop productivity with strong adverse effects on food security (*high confidence*). Progress has been achieved on managing risks to food production from current climate variability and near-term climate change, but this will not be sufficient to address long-term impacts of climate change. Adaptive agricultural processes such as collaborative, participatory research that includes scientists and farmers, strengthened communication systems for anticipating and responding to climate risks, and increased flexibility in livelihood options provide potential pathways for strengthening adaptive capacities. Climate change is a multiplier of existing health vulnerabilities including insufficient access to safe water and improved sanitation, food insecurity, and limited access to health care and education. Strategies that integrate consideration of climate change risks with land and water management and disaster risk reduction bolster resilient development. [22.3 to 22.4, 22.6]

***Europe*. Climate change will increase the likelihood of systemic failures across European countries caused by extreme climate events affecting multiple sectors (*medium confidence*).** Sea level rise and increases in extreme rainfall are projected to further increase coastal and river flood risks and without adaptive measures will substantially increase flood damages (i.e., people affected and economic losses); adaptation can prevent most of the projected damages (*high confidence*). Heat-related deaths and injuries are *likely* to increase, particularly in southern Europe (*medium confidence*). Climate change is *likely* to increase cereal crop yields in northern Europe (*medium confidence*) but decrease yields in southern Europe (*high confidence*). Climate change will increase irrigation needs in Europe, and future irrigation will be constrained by reduced runoff, demand from other sectors, and economic costs, with integrated water management a strategy for addressing competing demands. Hydropower production is *likely* to decrease in all sub-regions except Scandinavia. Climate change is *very likely* to cause changes in habitats and species, with local extinctions (*high confidence*), continental-scale shifts in species distributions (*medium confidence*), and significantly reduced alpine plant habitat (*high confidence*). Climate change is *likely* to entail the loss or displacement of coastal wetlands. The introduction and expansion of invasive species, especially those with high migration rates, from outside Europe is *likely* to increase with climate change (medium confidence). [23.2 to 23.9]

***Asia*. Climate change will cause declines in agricultural productivity in many sub-regions of Asia, for crops such as rice (*medium confidence*).** In Central Asia, cereal production in northern and eastern Kazakhstan could benefit from the longer growing season, warmer winters, and slight increase in winter precipitation, while droughts in western Turkmenistan and Uzbekistan could negatively affect cotton production, increase water demand for irrigation, and exacerbate desertification. The effectiveness of potential and practiced agricultural adaptation strategies is not well understood. Future projections of precipitation at sub-regional scales and thus of freshwater availability in most parts of Asia are uncertain (*low confidence* in projections), but increased water demand from population growth, increased water consumption per capita, and lack of good management will increase water scarcity challenges for most of the region (*medium confidence*). Adaptive responses include integrated water management strategies, such as development of water-saving technologies, increased water productivity, and water reuse. Extreme climate events will have an increasing impact on human health, security, livelihoods, and poverty, with the type and magnitude of impact varying across Asia (*high confidence*). In many parts of Asia, observed terrestrial impacts, such as permafrost degradation and shifts in plant species' distributions, growth rates, and timing of seasonal activities, will increase due to climate change projected during the 21st century. Coastal and marine systems in Asia, such as mangroves, seagrass beds, salt marshes, and coral reefs, are under increasing stress from climatic and non-climatic drivers. In the Asian Arctic, sea level rise interacting with projected changes in permafrost and the length of the ice-free season will increase rates of coastal erosion (*medium evidence*, *high agreement*). [24.4, 30.5]

***Australasia*. Without adaptation, further changes in climate, atmospheric carbon dioxide, and ocean acidity are projected to have substantial impacts on water resources, coastal ecosystems, infrastructure, health, agriculture, and biodiversity (*high confidence*).** Freshwater resources are projected to decline in far

Table TS.5 | Key regional risks from climate change and the potential for reducing risks through adaptation and mitigation. Key risks have been identified based on assessment of the relevant scientific, technical, and socioeconomic literature detailed in supporting chapter sections. Identification of key risks was based on expert judgment using the following specific criteria: large magnitude, high probability, or irreversibility of impacts; timing of impacts; persistent vulnerability or exposure contributing to risks; or limited potential to reduce risks through adaptation or mitigation. Each key risk is characterized as very low to very high for three timeframes: the present, near term (here, assessed over 2030–2040), and longer term (here, assessed over 2080–2100). The risk levels integrate probability and consequence over the widest possible range of potential outcomes, based on available literature. These potential outcomes result from the interaction of climate-related hazards, vulnerability, and exposure. Each risk level reflects total risk from climatic and non-climatic factors. For the near-term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially for different emission scenarios. For the longer-term era of climate options, risk levels are presented for two scenarios of global mean temperature increase (2°C and 4°C above preindustrial levels). These scenarios illustrate the potential for mitigation and adaptation to reduce the risks related to climate change. For the present, risk levels were estimated for current adaptation and a hypothetical highly adapted state, identifying where current adaptation deficits exist. For the two future timeframes, risk levels were estimated for a continuation of current adaptation and for a highly adapted state, representing the potential for and limits to adaptation. Climate-related drivers of impacts are indicated by icons. Key risks and risk levels vary across regions and over time, given differing socioeconomic development pathways, vulnerability and exposure to hazards, adaptive capacity, and risk perceptions. Risk levels are not necessarily comparable, especially across regions, because the assessment considers potential impacts and adaptation in different physical, biological, and human systems across diverse contexts. This assessment of risks acknowledges the importance of differences in values and objectives in interpretation of the assessed risk levels.



Africa

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation (Very low – Medium – Very high)
Compounded stress on water resources facing significant strain from overexploitation and degradation at present and increased demand in the future, with drought stress exacerbated in drought-prone regions of Africa (*high confidence*) [22.3, 22.4]	• Reducing non-climate stressors on water resources • Strengthening institutional capacities for demand management, groundwater assessment, integrated water-wastewater planning, and integrated land and water governance • Sustainable urban development		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Reduced crop productivity associated with heat and drought stress, with strong adverse effects on regional, national, and household livelihood and food security, also given increased pest and disease damage and flood impacts on food system infrastructure (*high confidence*) [22.3, 22.4]	• Technological adaptation responses (e.g., stress-tolerant crop varieties, irrigation, enhanced observation systems) • Enhancing smallholder access to credit and other critical production resources; Diversifying livelihoods • Strengthening institutions at local, national, and regional levels to support agriculture (including early warning systems) and gender-oriented policy • Agronomic adaptation responses (e.g., agroforestry, conservation agriculture)		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Changes in the incidence and geographic range of vector- and water-borne diseases due to changes in the mean and variability of temperature and precipitation, particularly along the edges of their distribution (*medium confidence*) [22.3]	• Achieving development goals, particularly improved access to safe water and improved sanitation, and enhancement of public health functions such as surveillance • Vulnerability mapping and early warning systems • Coordination across sectors • Sustainable urban development		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

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Europe

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Increased economic losses and people affected by flooding in river basins and coasts, driven by increasing urbanization, increasing sea levels, coastal erosion, and peak river discharges (*high confidence*) [23.2, 23.3, 23.7]	Adaptation can prevent most of the projected damages (*high confidence*). • Significant experience in hard flood-protection technologies and increasing experience with restoring wetlands • High costs for increasing flood protection • Potential barriers to implementation: demand for land in Europe and environmental and landscape concerns		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Increased water restrictions. Significant reduction in water availability from river abstraction and from groundwater resources, combined with increased water demand (e.g., for irrigation, energy and industry, domestic use) and with reduced water drainage and runoff as a result of increased evaporative demand, particularly in southern Europe (*high confidence*) [23.4, 23.7]	• Proven adaptation potential from adoption of more water-efficient technologies and of water-saving strategies (e.g., for irrigation, crop species, land cover, industries, domestic use) • Implementation of best practices and governance instruments in river basin management plans and integrated water management		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Increased economic losses and people affected by extreme heat events: impacts on health and well-being, labor productivity, crop production, air quality, and increasing risk of wildfires in southern Europe and in Russian boreal region (*medium confidence*) [23.3 to 23.7, Table 23-1]	• Implementation of warning systems • Adaptation of dwellings and workplaces and of transport and energy infrastructure • Reductions in emissions to improve air quality • Improved wildfire management • Development of insurance products against weather-related yield variations		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high

Asia

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Increased riverine, coastal, and urban flooding leading to widespread damage to infrastructure, livelihoods, and settlements in Asia (*medium confidence*) [24.4]	• Exposure reduction via structural and non-structural measures, effective land-use planning, and selective relocation • Reduction in the vulnerability of lifeline infrastructure and services (e.g., water, energy, waste management, food, biomass, mobility, local ecosystems, telecommunications) • Construction of monitoring and early warning systems; Measures to identify exposed areas, assist vulnerable areas and households, and diversify livelihoods • Economic diversification		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Increased risk of heat-related mortality (*high confidence*) [24.4]	• Heat health warning systems • Urban planning to reduce heat islands; Improvement of the built environment; Development of sustainable cities • New work practices to avoid heat stress among outdoor workers		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Increased risk of drought-related water and food shortage causing malnutrition (*high confidence*) [24.4]	• Disaster preparedness including early-warning systems and local coping strategies • Adaptive/integrated water resource management • Water infrastructure and reservoir development • Diversification of water sources including water re-use • More efficient use of water (e.g., improved agricultural practices, irrigation management, and resilient agriculture)		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high

southwest and far southeast mainland Australia (*high confidence*) and for some rivers in New Zealand (*medium confidence*). Rising sea levels and increasing heavy rainfall are projected to increase erosion and inundation, with consequent damages to many low-lying ecosystems, infrastructure, and housing (*high confidence*); increasing heat waves will increase risks to human health; rainfall changes and rising temperatures will shift agricultural production zones; and many native species will suffer from range contractions and some may face local or even global extinction. Uncertainty in projected rainfall changes remains large for many parts of Australia and New Zealand, which creates significant challenges for adaptation. Some sectors in some locations have the potential to benefit from projected changes in climate and increasing atmospheric CO_2, for example due to reduced energy demand for winter heating in New Zealand and southern parts of Australia, and due to forest growth in cooler regions except where soil nutrients or rainfall are limiting. Indigenous peoples in both Australia and New Zealand have higher than average exposure to climate change due to a heavy reliance on climate-sensitive primary industries and strong social connections to the natural environment, and face additional constraints to adaptation (*medium confidence*). [25.2, 25.3, 25.5 to 25.8, Boxes 25-1, 25-2, 25-5, and 25-8]

***North America*. Many climate-related hazards that carry risk, particularly related to severe heat, heavy precipitation, and declining snowpack, will increase in frequency and/or severity in North America in the next decades (*very high confidence*).** Climate

Table TS.5 (continued)

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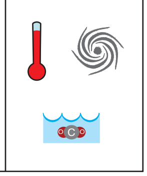
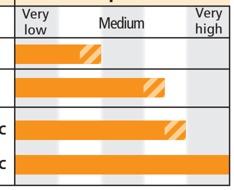
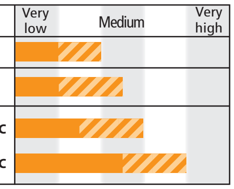
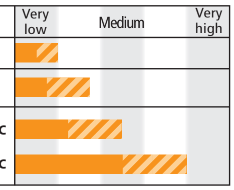
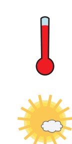
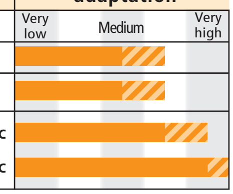
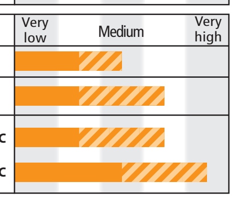
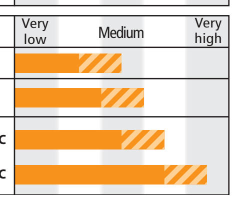
Australasia

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Significant change in community composition and structure of coral reef systems in Australia (*high confidence*) [25.6, 30.5, Boxes CC-CR and CC-OA]	• Ability of corals to adapt naturally appears limited and insufficient to offset the detrimental effects of rising temperatures and acidification. • Other options are mostly limited to reducing other stresses (water quality, tourism, fishing) and early warning systems; direct interventions such as assisted colonization and shading have been proposed but remain untested at scale.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (*high confidence*) [Table 25-1, Boxes 25-8 and 25-9]	• Significant adaptation deficit in some regions to current flood risk. • Effective adaptation includes land-use controls and relocation as well as protection and accommodation of increased risk to ensure flexibility.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damage towards the upper end of projected sea-level-rise ranges (*high confidence*) [25.6, 25.10, Box 25-1]	• Adaptation deficit in some locations to current coastal erosion and flood risk. Successive building and protection cycles constrain flexible responses. • Effective adaptation includes land-use controls and ultimately relocation as well as protection and accommodation.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

North America

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Wildfire-induced loss of ecosystem integrity, property loss, human morbidity, and mortality as a result of increased drying trend and temperature trend (*high confidence*) [26.4, 26.8, Box 26-2]	• Some ecosystems are more fire-adapted than others. Forest managers and municipal planners are increasingly incorporating fire protection measures (e.g., prescribed burning, introduction of resilient vegetation). Institutional capacity to support ecosystem adaptation is limited. • Adaptation of human settlements is constrained by rapid private property development in high-risk areas and by limited household-level adaptive capacity. • Agroforestry can be an effective strategy for reduction of slash and burn practices in Mexico.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Heat-related human mortality (*high confidence*) [26.6, 26.8]	• Residential air conditioning (A/C) can effectively reduce risk. However, availability and usage of A/C is highly variable and is subject to complete loss during power failures. Vulnerable populations include athletes and outdoor workers for whom A/C is not available. • Community- and household-scale adaptations have the potential to reduce exposure to heat extremes via family support, early heat warning systems, cooling centers, greening, and high-albedo surfaces.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Urban floods in riverine and coastal areas, inducing property and infrastructure damage; supply chain, ecosystem, and social system disruption; public health impacts; and water quality impairment, due to sea level rise, extreme precipitation, and cyclones (*high confidence*) [26.2 to 26.4, 26.8]	• Implementing management of urban drainage is expensive and disruptive to urban areas. • Low-regret strategies with co-benefits include less impervious surfaces leading to more groundwater recharge, green infrastructure, and rooftop gardens. • Sea level rise increases water elevations in coastal outfalls, which impedes drainage. In many cases, older rainfall design standards are being used that need to be updated to reflect current climate conditions. • Conservation of wetlands, including mangroves, and land-use planning strategies can reduce the intensity of flood events.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

change will amplify risks to water resources already affected by non-climatic stressors, with potential impacts associated with decreased snowpack, decreased water quality, urban flooding, and decreased water supplies for urban areas and irrigation (*high confidence*). More adaptation options are available to address water supply deficits than flooding and water quality concerns (*medium confidence*). Ecosystems are under increasing stress from rising temperatures, CO_2 concentrations, and sea levels, with particular vulnerability to climate extremes (*very high confidence*). In many cases, climate stresses exacerbate other anthropogenic influences on ecosystems, including land use changes, non-native species, and pollution. Projected increases in temperature, reductions in precipitation in some regions, and increased frequency of extreme events would result in net productivity declines in major North American crops by the end of the 21st century without adaptation, although some regions, particularly in the north, may benefit. Adaptation, often with mitigation co-benefits, could offset projected negative yield impacts for many crops at 2°C global mean temperature increase above preindustrial levels, with reduced effectiveness of adaptation at 4°C (*high confidence*). Although larger urban centers would have higher adaptive capacities, high population density, inadequate infrastructures, lack of institutional capacity, and degraded natural environments increase future climate risks from heat waves, droughts, storms, and sea level rise (*medium evidence*, *high agreement*). Future risks from climate extremes can be reduced, for example through targeted and sustainable air conditioning, more effective warning and response systems, enhanced pollution controls, urban

Table TS.5 (continued)

Continued next page →

Central and South America

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Water availability in semi-arid and glacier-melt-dependent regions and Central America; flooding and landslides in urban and rural areas due to extreme precipitation (*high confidence*) [27.3]	• Integrated water resource management • Urban and rural flood management (including infrastructure), early warning systems, better weather and runoff forecasts, and infectious disease control		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
Decreased food production and food quality (*medium confidence*) [27.3]	• Development of new crop varieties more adapted to climate change (temperature and drought) • Offsetting of human and animal health impacts of reduced food quality • Offsetting of economic impacts of land-use change • Strengthening traditional indigenous knowledge systems and practices		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
Spread of vector-borne diseases in altitude and latitude (*high confidence*) [27.3]	• Development of early warning systems for disease control and mitigation based on climatic and other relevant inputs. Many factors augment vulnerability. • Establishing programs to extend basic public health services		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high Long term 2°C: not available Long term 4°C: not available

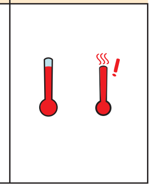
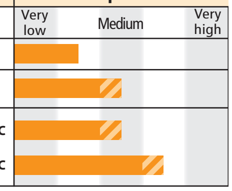
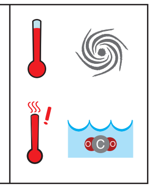
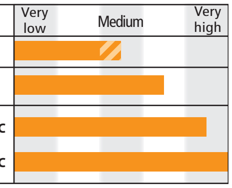
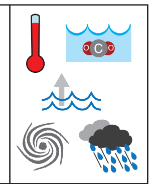
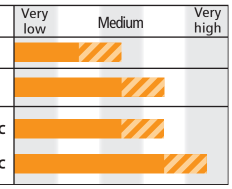
Polar Regions

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Risks for freshwater and terrestrial ecosystems (*high confidence*) and marine ecosystems (*medium confidence*), due to changes in ice, snow cover, permafrost, and freshwater/ocean conditions, affecting species´ habitat quality, ranges, phenology, and productivity, as well as dependent economies [28.2 to 28.4]	• Improved understanding through scientific and indigenous knowledge, producing more effective solutions and/or technological innovations • Enhanced monitoring, regulation, and warning systems that achieve safe and sustainable use of ecosystem resources • Hunting or fishing for different species, if possible, and diversifying income sources		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
Risks for the health and well-being of Arctic residents, resulting from injuries and illness from the changing physical environment, food insecurity, lack of reliable and safe drinking water, and damage to infrastructure, including infrastructure in permafrost regions (*high confidence*) [28.2 to 28.4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Shifting resource bases, land use, and/or settlement areas		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
Unprecedented challenges for northern communities due to complex inter-linkages between climate-related hazards and societal factors, particularly if rate of change is faster than social systems can adapt (*high confidence*) [28.2 to 28.4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Adaptive co-management responses developed through the settlement of land claims		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high

Small Islands

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Loss of livelihoods, coastal settlements, infrastructure, ecosystem services, and economic stability (*high confidence*) [29.6, 29.8, Figure 29-4]	• Significant potential exists for adaptation in islands, but additional external resources and technologies will enhance response. • Maintenance and enhancement of ecosystem functions and services and of water and food security • Efficacy of traditional community coping strategies is expected to be substantially reduced in the future.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
The interaction of rising global mean sea level in the 21st century with high-water-level events will threaten low-lying coastal areas (*high confidence*) [29.4, Table 29-1; WGI AR5 13.5, Table 13.5]	• High ratio of coastal area to land mass will make adaptation a significant financial and resource challenge for islands. • Adaptation options include maintenance and restoration of coastal landforms and ecosystems, improved management of soils and freshwater resources, and appropriate building codes and settlement patterns.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high

Table TS.5 (continued)

The Ocean				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Distributional shift in fish and invertebrate species, and decrease in fisheries catch potential at low latitudes, e.g., in equatorial upwelling and coastal boundary systems and sub-tropical gyres (*high confidence*) [6.3, 30.5, 30.6, Tables 6-6 and 30-3, Box CC-MB]	• Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their changes in distribution to maintain temperatures. • Human adaptation options: Large-scale translocation of industrial fishing activities following the regional decreases (low latitude) vs. possibly transient increases (high latitude) in catch potential; Flexible management that can react to variability and change; Improvement of fish resilience to thermal stress by reducing other stressors such as pollution and eutrophication; Expansion of sustainable aquaculture and the development of alternative livelihoods in some regions.		Present Near term (2030–2040) Long term 2°C / 4°C (2080–2100)	
Reduced biodiversity, fisheries abundance, and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, exacerbated by ocean acidification, e.g., in coastal boundary systems and sub-tropical gyres (*high confidence*) [5.4, 6.4, 30.3, 30.5, 30.6, Tables 6-6 and 30-3, Box CC-CR]	• Evidence of rapid evolution by corals is very limited. Some corals may migrate to higher latitudes, but entire reef systems are not expected to be able to track the high rates of temperature shifts. • Human adaptation options are limited to reducing other stresses, mainly by enhancing water quality, and limiting pressures from tourism and fishing. These options will delay human impacts of climate change by a few decades, but their efficacy will be severely reduced as thermal stress increases.		Present Near term (2030–2040) Long term 2°C / 4°C (2080–2100)	
Coastal inundation and habitat loss due to sea level rise, extreme events, changes in precipitation, and reduced ecological resilience, e.g., in coastal boundary systems and sub-tropical gyres (*medium* to *high confidence*) [5.5, 30.5, 30.6, Tables 6-6 and 30-3, Box CC-CR]	• Human adaptation options are limited to reducing other stresses, mainly by reducing pollution and limiting pressures from tourism, fishing, physical destruction, and unsustainable aquaculture. • Reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients • Increased mangrove, coral reef, and seagrass protection, and restoration to protect numerous ecosystem goods and services such as coastal protection, tourist value, and fish habitat		Present Near term (2030–2040) Long term 2°C / 4°C (2080–2100)	

planning strategies, and resilient health infrastructure (*high confidence*). [26.3 to 26.6, 26.8]

***Central and South America*. Despite improvements, high and persistent levels of poverty in most countries result in high vulnerability to climate variability and change (*high confidence*).** Climate change impacts on agricultural productivity are expected to exhibit large spatial variability, for example with sustained or increased productivity through mid-century in southeast South America and decreases in productivity in the near term (by 2030) in Central America, threatening food security of the poorest populations (*medium confidence*). Reduced precipitation and increased evapotranspiration in semi-arid regions will increase risks from water-supply shortages, affecting cities, hydropower generation, and agriculture (*high confidence*). Ongoing adaptation strategies include reduced mismatch between water supply and demand, and water-management and coordination reforms (*medium confidence*). Conversion of natural ecosystems, a driver of anthropogenic climate change, is the main cause of biodiversity and ecosystem loss (*high confidence*). Climate change is expected to increase rates of species extinction (*medium confidence*). In coastal and marine systems, sea level rise and human stressors increase risks for fish stocks, corals, mangroves, recreation and tourism, and control of diseases (*high confidence*). Climate change will exacerbate future health risks given regional population growth rates and vulnerabilities due to pollution, food insecurity in poor regions, and existing health, water, sanitation, and waste collection systems (*medium confidence*). [27.2, 27.3]

***Polar Regions*. Climate change and often-interconnected non-climate-related drivers, including environmental changes, demography, culture, and economic development, interact in the Arctic to determine physical, biological, and socioeconomic risks, with rates of change that may be faster than social systems can adapt (*high confidence*).** Thawing permafrost and changing precipitation patterns have the potential to affect infrastructure and related services, with particular risks for residential buildings, for example in Arctic cities and small rural settlements. Climate change will especially impact Arctic communities that have narrowly based economies limiting adaptive choices. Increased Arctic navigability and expanded land- and freshwater-based transportation networks will increase economic opportunities. Impacts on the informal, subsistence-based economy will include changing sea ice conditions that increase the difficulty of hunting marine mammals. Polar bears have been and will be affected by loss of annual ice over continental shelves, decreased ice duration, and decreased ice thickness. Already, accelerated rates of change in permafrost thaw, loss of coastal sea ice, sea level rise, and increased intensity of weather extremes are forcing relocation of some indigenous communities in Alaska (*high confidence*). In the Arctic and Antarctic, some marine species will shift their ranges in response to changing ocean and sea ice conditions (*medium confidence*). Climate change will increase the vulnerability of terrestrial ecosystems to invasions by non-indigenous species (*high confidence*). [6.3, 6.5, 28.2 to 28.4]

***Small Islands*. Small islands have high vulnerability to climatic and non-climatic stressors (*high confidence*).** Diverse physical and human attributes and their sensitivity to climate-related drivers lead to variable climate change risk profiles and adaptation from one island region to another and among countries in the same region. Risks can originate from transboundary interactions, for example associated with existing and future invasive species and human health challenges. Sea level rise poses one of the most widely recognized climate change threats to low-lying coastal areas on islands and atolls. Projected sea level rise at the end of the 21st century, superimposed on extreme-sea-level events, presents severe coastal flooding and erosion risks for low-lying coastal areas and atoll islands. Wave over-wash will degrade groundwater resources. Coral reef ecosystem degradation associated with increasing sea surface temperature and ocean acidification will

Table TS.6 | Observed and projected future changes in some types of temperature and precipitation extremes over 26 sub-continental regions as defined in the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX). Confidence levels are indicated by symbol color. Likelihood terms are given only for *high* or *very high confidence* statements. Observed trends in temperature and precipitation extremes, including dryness and drought, are generally calculated from 1950, using 1961–1990 as the reference period, unless otherwise indicated. Future changes are derived from global and regional climate model projections for 2071–2100 compared with 1961–1990 or for 2080–2100 compared with 1980–2000. Table entries are summaries of information in SREX Tables 3-2 and 3-3 supplemented with or superseded by material from WGI AR5 2.6, 14.8, and Table 2.13 and WGII AR5 Table 25-1. The source(s) of information for each entry are indicated by superscripts: (a) SREX Table 3-2; (b) SREX Table 3-3; (c) WGI AR5 2.6 and Table 2.13; (d) WGI AR5 14.8; (e) WGII AR5 Table 25-1. [Tables 21-7 and SM21-2, Figure 21-4]

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
West North America WNA, 3	*Very likely* large increases in hot days (large decreases in cool days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends. General increase, decrease in some areas[a]	Increase in 20-year return value of annual maximum daily precipitation and other metrics over northern part of the region (Canada)[b] Less confidence in southern part of the region, due to inconsistent signal in these other metrics[b]	No change or overall slight decrease in dryness[a]	Inconsistent signal[b]
Central North America CNA, 4	Spatially varying trends: small increases in hot days in the north, decreases in the south[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Very likely* increase since 1950[a]	Increase in 20-year return value of annual maximum daily precipitation[b] Inconsistent signal in other heavy precipitation days metrics[b]	*Likely* decrease[a, c]	Increase in consecutive dry days and soil moisture in southern part of central North America[b] Inconsistent signal in the rest of the region[b]
East North America ENA, 5	Spatially varying trends. Overall increases in hot days (decreases in cool days), opposite or insignificant signal in a few areas[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Very likely* increase since 1950[a]	Increase in 20-year return value of annual maximum daily precipitation. Additional metrics support an increase in heavy precipitation over northern part of the region.[b] No signal or inconsistent signal in these other metrics in the southern part of the region[b]	Slight decrease in dryness since 1950[a]	Inconsistent signal in consecutive dry days, some consistent decrease in soil moisture[b]
Alaska/ Northwest Canada ALA, 1	*Very likely* large increases in hot days (decreases in cool days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Slight tendency for increase[a] No significant trend in southern Alaska[a]	*Likely* increase in heavy precipitation[b]	Inconsistent trends[a] Increase in dryness in part of the region[a]	Inconsistent signal[b]
East Canada, Greenland, Iceland CGI, 2	*Likely* increases in hot days (decreases in cool days) in some areas, decrease in hot days (increase in cool days) in others[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Increase in a few areas[a]	*Likely* increase in heavy precipitation[b]	Insufficent evidence[a]	Inconsistent signal[b]
Northern Europe NEU, 11	Increase in hot days (decrease in cool days), but generally not significant at the local scale[a]	*Very likely* increase in hot days (decrease in cool days) [but smaller trends than in central and southern Europe][b]	Increase in winter in some areas, but often insignificant or inconsistent trends at sub-regional scale, particularly in summer[a]	*Likely* increase in 20-year return value of annual maximum daily precipitation. *Very likely* increases in heavy preciptation intensity and frequency in winter in the north[b]	Spatially varying trends. Overall only slight or no increase in dryness, slight decrease in dryness in part of the region[a]	No major changes in dryness[b]

Symbols

Increasing trend or signal — Decreasing trend or signal — Both increasing and decreasing trend or signal — Inconsistent trend or signal or insufficient evidence — No change or only slight change

Level of confidence in findings

Low confidence — *Medium confidence* — *High confidence*

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Table TS.6 (continued)

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
Central Europe CEU, 12	*Likely* overall increase in hot days (decrease in cool days) in most regions. *Very likely* increase in hot days (*likely* decrease in cool days) in west-central Europe[a] Lower confidence in trends in east-central Europe (due to lack of literature, partial lack of access to observations, overall weaker signals, and change point in trends)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Increase in part of the region, in particular central western Europe and European Russia, especially in winter.[a] Insignificant or inconsistent trends elsewhere, in particular in summer[a]	*Likely* increase in 20-year return value of annual maximum daily precipitation. Additional metrics support an increase in heavy precipitation in large part of the region in winter.[b] Less confidence in summer, due to inconsistent evidence[b]	Spatially varying trends. Increase in dryness in part of the region but some regional variation in dryness trends and dependence of trends on studies considered (index, time period)[a]	Increase in dryness in central Europe and increase in short-term droughts[b]
Southern Europe and Mediterranean MED, 13	*Likely* increase in hot days (decrease in cool days) in most of the region. Some regional and temporal variations in the significance of the trends. *Likely* strongest and most significant trends in Iberian peninsula and southern France[a] Smaller or less significant trends in southeastern Europe and Italy due to change point in trends, strongest increase in hot days since 1976[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Inconsistent trends across the region and across studies[a]	Inconsistent changes and/or regional variations[b]	Overall increase in dryness, *likely* increase in the Mediterranean[a, c]	Increase in dryness. Consistent increase in area of drought[b, d]
West Africa WAF, 15	Significant increase in temperature of hottest day and coolest day in some parts[a] Insufficient evidence in other parts[a]	*Likely* increase in hot days (decrease in cool days)[b]	Rainfall intensity increased[a]	Slight or no change in heavy precipitation indicators in most areas[b] Low model agreement in northern areas[b]	*Likely* increase but 1970s Sahel drought dominates the trend; greater inter-annual variation in recent years[a, c]	Inconsistent signal[b]
East Africa EAF, 16	Lack of evidence due to lack of literature and spatially non-uniform trends[a] Increases in hot days in southern tip (decreases in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Insufficient evidence[a]	*Likely* increase in heavy precipitation[b]	Spatially varying trends in dryness[a]	Decreasing dryness in large areas[b]
Southern Africa SAF, 17	*Likely* increase in hot days (decrease in cool days)[a, c]	*Likely* increase in hot days (decrease in cool days)[b]	Increases in more regions than decreases but spatially varying trends[a,c]	Lack of agreement in signal for region as a whole[b] Some evidence of increase in heavy precipitation in southeast regions[b]	General increase in dryness[a]	Increase in dryness, except eastern part[b, d] Consistent increase in area of drought[b]
Sahara SAH, 14	Lack of literature[a]	*Likely* increase in hot days (decrease in cool days)[b]	Insufficient evidence[a]	*Low agreement*[b]	Limited data, spatial variation of the trends[a]	Inconsistent signal of change[b]
Central America and Mexico CAM, 6	Increases in the number of hot days, decreases in the number of cool days[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends. Increase in many areas, decrease in a few others[a]	Inconsistent trends[b]	Varying and inconsistent trends[a]	Increase in dryness in Central America and Mexico, with less confidence in trend in extreme south of region[b]

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Table TS.6 (continued)

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
Amazon AMZ, 7	Insufficient evidence to identify trends[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Increase in many areas, decrease in a few[a]	Tendency for increases in heavy precipitation events in some metrics[b]	Decrease in dryness for much of the region. Some opposite trends and inconsistencies[a]	Inconsistent signals[b]
Northeastern Brazil NEB, 8	Increases in the number of hot days[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Increase in many areas, decrease in a few[a]	Slight or no change[b]	Varying and inconsistent trends[a]	Increase in dryness[b]
Southeastern South America SSA, 10	Spatially varying trends (increases in hot days in some areas, decreases in others)[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Increase in northern areas[a] Insufficient evidence in southern areas[a]	Increases in northern areas[b] Insufficient evidence in southern areas[b]	Varying and inconsistent trends[a]	Inconsistent signals[b]
West Coast South America WSA, 9	Spatially varying trends (increases in hot days in some areas, decreases in others)[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Decrease in many areas, increase in a few areas[a]	Increases in tropics[b] *Low confidence* in extratropics[b]	Varying and inconsistent trends[a]	Decrease in consecutive dry days in the tropics, and increase in the extratropics[b] Increase in consecutive dry days and soil moisture in southwest South America[b]
North Asia NAS, 18	*Likely* increases in hot days (decreases in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Increase in some regions, but spatial variation[a]	*Likely* increase in heavy precipitation for most regions[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
Central Asia CAS, 20	*Likely* increases in hot days (decreases in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends[a]	Inconsistent signal in models[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
East Asia EAS, 22	*Likely* increases in hot days (decreases in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends[a]	Increases in heavy precipitation across the region[b]	Tendency for increased dryness[a]	Inconsistent signal of change[b]
Southeast Asia SEA, 24	Increases in hot days (decreases in cool days) for northern areas[a] Insufficient evidence for Malay Archipelago[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends, partial lack of evidence[a]	Increases in most metrics over most (especially non-continental) regions. One metric shows inconsistent signals of change.[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
South Asia SAS, 23	Increase in hot days (decrease in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Mixed signal in India[a]	More frequent and intense heavy precipitation days over parts of South Asia. Either no change or some consistent increases in other metrics[b]	Inconsistent signal for different studies and indices[a]	Inconsistent signal of change[b]
West Asia WAS, 19	*Very likely* increase in hot days (decrease in cool days *more likely than not*)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Decrease in heavy precipitation events[a]	Inconsistent signal of change[b]	Lack of studies, mixed results[a]	Inconsistent signal of change[b]
Tibetan Plateau TIB, 21	*Likely* increase in hot days (decrease in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Insufficient evidence[a]	Increase in heavy precipitation[b]	Insufficient evidence. Tendency to decreased dryness[a]	Inconsistent signal of change[b]
North Australia NAU, 25	*Likely* increase in hot days (decrease in cool days). Weaker trends in northwest[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends, which mostly reflect changes in mean rainfall[e]	Increase in most regions in the intensity of extreme (i.e., current 20-year return period) heavy rainfall events[e]	No significant change in drought occurrence over Australia (defined using rainfall anomalies)[e]	Inconsistent signal[b]

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Table TS.6 (continued)

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
South Australia/ New Zealand SAU, 26	*Very likely* increase in hot days (decrease in cool days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends in southern Australia, which mostly reflect changes in mean rainfall[e] Spatially varying trends in New Zealand, which mostly reflect changes in mean rainfall[e]	Increase in most regions in the intensity of extreme (i.e., current 20-year return period) heavy rainfall events[e]	No significant change in drought occurrence over Australia (defined using rainfall anomalies)[e] No trend in drought occurrence over New Zealand (defined using a soil–water balance model) since 1972[e]	Increase in drought frequency in southern Australia, and in many regions of New Zealand[e]

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negatively impact island communities and livelihoods, given the dependence of island communities on coral reef ecosystems for coastal protection, subsistence fisheries, and tourism. [29.3 to 29.5, 29.9, 30.5, Figure 29-1, Table 29-3, Box CC-CR]

***The Ocean*. Warming will increase risks to ocean ecosystems (*high confidence*).** Coral reefs within coastal boundary systems, semi-enclosed seas, and subtropical gyres are rapidly declining as a result of local non-climatic stressors (i.e., coastal pollution, overexploitation) and climate change. Projected increases in mass coral bleaching and mortality will alter or eliminate ecosystems, increasing risks to coastal livelihoods and food security (*medium* to *high confidence*). An analysis of the CMIP5 ensemble projects loss of coral reefs from most sites globally to be *very likely* by 2050 under mid to high rates of ocean warming. Reducing non-climatic stressors represents an opportunity to strengthen ecological resilience. The highly productive high-latitude spring bloom systems in the northeastern Atlantic are responding to warming (*medium evidence*, *high agreement*), with the greatest changes being observed since the late 1970s in the phenology, distribution, and abundance of plankton assemblages, and the reorganization of fish assemblages, with a range of consequences for fisheries (*high confidence*). Projected warming increases the likelihood of greater thermal stratification in some regions, which can lead to reduced O_2 ventilation and encourage the formation of hypoxic zones, especially in the Baltic and Black Seas (*medium confidence*). Changing surface winds and waves, sea level, and storm intensity will increase the vulnerability of ocean-based industries such as shipping, energy, and mineral extraction. New opportunities as well as international issues over access to resources and vulnerability may accompany warming waters particularly at high latitudes. [5.3, 5.4, 6.4, 28.2, 28.3, 30.3, 30.5, 30.6, Table 30-1, Figures 30-4 and 30-10, Boxes 6-1, CC-CR, and CC-MB]

Understanding of extreme events and their interactions with climate change is particularly important for managing risks in a regional context. Table TS.6 provides a summary of observed and projected trends in some types of temperature and precipitation extremes.

C: MANAGING FUTURE RISKS AND BUILDING RESILIENCE

Managing the risks of climate change involves adaptation and mitigation decisions with implications for future generations, economies, and environments. Figure TS.12 provides an overview of responses for addressing risk related to climate change.

Starting with principles for effective adaptation, this section evaluates the ways that interlinked human and natural systems can build resilience through adaptation, mitigation, and sustainable development. It describes understanding of climate-resilient pathways, of incremental versus transformational changes, and of limits to adaptation, and it considers co-benefits, synergies, and trade-offs among mitigation, adaptation, and development.

C-1. Principles for Effective Adaptation

The report assesses a wide variety of approaches for reducing and managing risks and building resilience. Strategies and approaches to climate change adaptation include efforts to decrease vulnerability or exposure and/or increase resilience or adaptive capacity. Mitigation is assessed in the WGIII AR5. Specific examples of responses to climate change are presented in Table TS.7.

Adaptation is place- and context-specific, with no single approach for reducing risks appropriate across all settings (*high confidence*). Effective risk reduction and adaptation strategies consider the dynamics of vulnerability and exposure and their linkages with socioeconomic processes, sustainable development, and climate change. [2.1, 8.3, 8.4, 13.1, 13.3, 13.4, 15.2, 15.3, 15.5, 16.2, 16.3, 16.5, 17.2, 17.4, 19.6, 21.3, 22.4, 26.8, 26.9, 29.6, 29.8]

Adaptation planning and implementation can be enhanced through complementary actions across levels, from individuals to governments (*high confidence*). National governments can coordinate adaptation efforts of local and subnational governments, for example by protecting vulnerable groups, by supporting economic diversification, and by providing information, policy and legal frameworks, and financial support (*robust evidence*, *high agreement*). Local government and the private sector are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities, households, and civil society and in managing risk information and financing (*medium evidence*, *high agreement*). [2.1 to 2.4, 3.6, 5.5, 8.3, 8.4, 9.3, 9.4, 14.2, 15.2, 15.3, 15.5, 16.2 to 16.5, 17.2, 17.3, 22.4, 24.4, 25.4, 26.8, 26.9, 30.7, Tables 21-1, 21-5, and 21-6, Box 16-2]

A first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate variability (*high confidence*). Strategies include actions with co-benefits for other objectives. Available strategies and actions can increase resilience across a range of possible future climates while helping to improve human health, livelihoods, social and economic well-being, and environmental quality. Examples of adaptation strategies that also strengthen livelihoods, enhance development, and reduce poverty include improved social protection, improved water and land governance, enhanced water storage and services, greater involvement in planning, and elevated attention to urban and peri-urban areas heavily affected by migration of poor people. See Table TS.7. [3.6, 8.3, 9.4, 14.3, 15.2, 15.3, 17.2, 20.4, 20.6, 22.4, 24.4, 24.5, 25.4, 25.10, 27.3 to 27.5, 29.6, Boxes 25-2 and 25-6]

Adaptation planning and implementation at all levels of governance are contingent on societal values, objectives, and risk perceptions (*high confidence*). Recognition of diverse interests, circumstances, social-cultural contexts, and expectations can

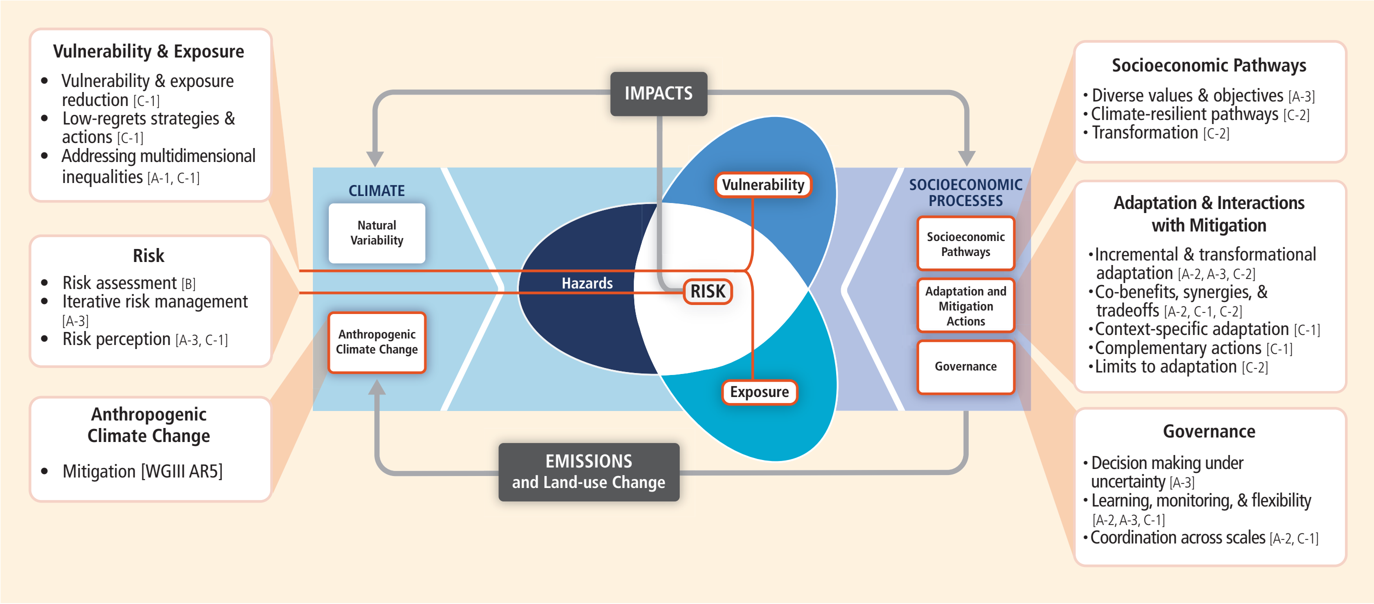


Figure TS.12 | The solution space. Core concepts of the WGII AR5, illustrating overlapping entry points and approaches, as well as key considerations, in managing risks related to climate change, as assessed in the report and presented throughout this summary. Bracketed references indicate sections of the summary with corresponding assessment findings.

Table TS.7 | Approaches for managing the risks of climate change. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Mitigation is considered essential for managing the risks of climate change. It is not addressed in this table as mitigation is the focus of WGIII AR5. Examples are presented in no specific order and can be relevant to more than one category. [14.2, 14.3, Table 14-1]

Overlapping Approaches	Category	Examples	Chapter Reference(s)
Vulnerability & Exposure Reduction through development, planning, & practices including many low-regrets measures	Human development	Improved access to education, nutrition, health facilities, energy, safe housing & settlement structures, & social support structures; Reduced gender inequality & marginalization in other forms.	8.3, 9.3, 13.1 to 13.3, 14.2, 14.3, 22.4
	Poverty alleviation	Improved access to & control of local resources; Land tenure; Disaster risk reduction; Social safety nets & social protection; Insurance schemes.	8.3, 8.4, 9.3, 13.1 to 13.3
	Livelihood security	Income, asset, & livelihood diversification; Improved infrastructure; Access to technology & decision-making fora; Increased decision-making power; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	7.5, 9.4, 13.1 to 13.3, 22.3, 22.4, 23.4, 26.5, 27.3, 29.6, Table SM24-7
	Disaster risk management	Early warning systems; Hazard & vulnerability mapping; Diversifying water resources; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements.	8.2 to 8.4, 11.7, 14.3, 15.4, 22.4, 24.4, 26.6, 28.4, Table 3-3, Box 25-1
	Ecosystem management	Maintaining wetlands & urban green spaces; Coastal afforestation; Watershed & reservoir management; Reduction of other stressors on ecosystems & of habitat fragmentation; Maintenance of genetic diversity; Manipulation of disturbance regimes; Community-based natural resource management.	4.3, 4.4, 8.3, 22.4, Table 3-3, Boxes 4-3, 8-2, 15-1, 25-8, 25-9, & CC-EA
	Spatial or land-use planning	Provisioning of adequate housing, infrastructure, & services; Managing development in flood prone & other high risk areas; Urban planning & upgrading programs; Land zoning laws; Easements; Protected areas.	4.4, 8.1 to 8.4, 22.4, 23.7, 23.8, 27.3, Box 25-8
Adaptation including incremental & transformational adjustments	Structural/physical	***Engineered & built-environment options***: Sea walls & coastal protection structures; Flood levees; Water storage; Improved drainage; Flood & cyclone shelters; Building codes & practices; Storm & wastewater management; Transport & road infrastructure improvements; Floating houses; Power plant & electricity grid adjustments.	3.5, 3.6, 5.5, 8.2, 8.3, 10.2, 11.7, 23.3, 24.4, 25.7, 26.3, 26.8, Boxes 15-1, 25-1, 25-2, & 25-8
		Technological options: New crop & animal varieties; Indigenous, traditional, & local knowledge, technologies, & methods; Efficient irrigation; Water-saving technologies; Desalinization; Conservation agriculture; Food storage & preservation facilities; Hazard & vulnerability mapping & monitoring; Early warning systems; Building insulation; Mechanical & passive cooling; Technology development, transfer, & diffusion.	7.5, 8.3, 9.4, 10.3, 15.4, 22.4, 24.4, 26.3, 26.5, 27.3, 28.2, 28.4, 29.6, 29.7, Tables 3-3 & 15-1, Boxes 20-5 & 25-2
		Ecosystem-based options: Ecological restoration; Soil conservation; Afforestation & reforestation; Mangrove conservation & replanting; Green infrastructure (e.g., shade trees, green roofs); Controlling overfishing; Fisheries co-management; Assisted species migration & dispersal; Ecological corridors; Seed banks, gene banks, & other *ex situ* conservation; Community-based natural resource management.	4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 15.4, 22.4, 23.6, 23.7, 24.4, 25.6, 27.3, 28.2, 29.7, 30.6, Boxes 15-1, 22-2, 25-9, 26-2, & CC-EA
		Services: Social safety nets & social protection; Food banks & distribution of food surplus; Municipal services including water & sanitation; Vaccination programs; Essential public health services; Enhanced emergency medical services.	3.5, 3.6, 8.3, 9.3, 11.7, 11.9, 22.4, 29.6, Box 13-2
	Institutional	***Economic options***: Financial incentives; Insurance; Catastrophe bonds; Payments for ecosystem services; Pricing water to encourage universal provision and careful use; Microfinance; Disaster contingency funds; Cash transfers; Public-private partnerships.	8.3, 8.4, 9.4, 10.7, 11.7, 13.3, 15.4, 17.5, 22.4, 26.7, 27.6, 29.6, Box 25-7
		Laws & regulations: Land zoning laws; Building standards & practices; Easements; Water regulations & agreements; Laws to support disaster risk reduction; Laws to encourage insurance purchasing; Defined property rights & land tenure security; Protected areas; Fishing quotas; Patent pools & technology transfer.	4.4, 8.3, 9.3, 10.5, 10.7, 15.2, 15.4, 17.5, 22.4, 23.4, 23.7, 24.4, 25.4, 26.3, 27.3, 30.6, Table 25-2, Box CC-CR
		National & government policies & programs: National & regional adaptation plans including mainstreaming; Sub-national & local adaptation plans; Economic diversification; Urban upgrading programs; Municipal water management programs; Disaster planning & preparedness; Integrated water resource management; Integrated coastal zone management; Ecosystem-based management; Community-based adaptation.	2.4, 3.6, 4.4, 5.5, 6.4, 7.5, 8.3, 11.7, 15.2 to 15.5, 22.4, 23.7, 25.4, 25.8, 26.8, 26.9, 27.3, 27.4, 29.6, Tables 9-2 & 17-1, Boxes 25-1, 25-2, & 25-9
	Social	***Educational options***: Awareness raising & integrating into education; Gender equity in education; Extension services; Sharing indigenous, traditional, & local knowledge; Participatory action research & social learning; Knowledge-sharing & learning platforms.	8.3, 8.4, 9.4, 11.7, 12.3, 15.2 to 15.4, 22.4, 25.4, 28.4, 29.6, Tables 15-1 & 25-2
		Informational options: Hazard & vulnerability mapping; Early warning & response systems; Systematic monitoring & remote sensing; Climate services; Use of indigenous climate observations; Participatory scenario development; Integrated assessments.	2.4, 5.5, 8.3, 8.4, 9.4, 11.7, 15.2 to 15.4, 22.4, 23.5, 24.4, 25.8, 26.6, 26.8, 27.3, 28.2, 28.5, 30.6, Table 25-2, Box 26-3
		Behavioral options: Household preparation & evacuation planning; Migration; Soil & water conservation; Storm drain clearance; Livelihood diversification; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	5.5, 7.5, 9.4, 12.4, 22.3, 22.4, 23.4, 23.7, 25.7, 26.5, 27.3, 29.6, Table SM24-7, Box 25-5
Transformation	Spheres of change	***Practical***: Social & technical innovations, behavioral shifts, or institutional & managerial changes that produce substantial shifts in outcomes.	8.3, 17.3, 20.5, Box 25-5
		Political: Political, social, cultural, & ecological decisions & actions consistent with reducing vulnerability & risk & supporting adaptation, mitigation, & sustainable development.	14.2, 14.3, 20.5, 25.4, 30.7, Table 14-1
		Personal: Individual & collective assumptions, beliefs, values, & worldviews influencing climate-change responses.	14.2, 14.3, 20.5, 25.4, Table 14-1

benefit decision-making processes. Awareness that climate change may exceed the adaptive capacity of some people and ecosystems may have ethical implications for mitigation decisions and investments. Economic analysis of adaptation is moving away from a unique emphasis on efficiency, market solutions, and benefit/cost analysis to include consideration of non-monetary and non-market measures, risks, inequities, behavioral biases, barriers and limits, and ancillary benefits and costs. [2.2 to 2.4, 9.4, 12.3, 13.2, 15.2, 16.2 to 16.4, 16.6, 16.7, 17.2, 17.3, 21.3, 22.4, 24.4, 24.6, 25.4, 25.8, 26.9, 28.2, 28.4, Table 15-1, Boxes 16-1, 16-4, and 25-7]

Indigenous, local, and traditional knowledge systems and practices, including indigenous peoples' holistic view of community and environment, are a major resource for adapting to climate change (*robust evidence*, *high agreement*). Natural resource dependent communities, including indigenous peoples, have a long history of adapting to highly variable and changing social and ecological conditions. But the salience of indigenous, local, and traditional knowledge will be challenged by climate change impacts. Such forms of knowledge have not been used consistently in existing adaptation efforts. Integrating such forms of knowledge with existing practices increases the effectiveness of adaptation. [9.4, 12.3, 15.2, 22.4, 24.4, 24.6, 25.8, 28.2, 28.4, Table 15-1]

Decision support is most effective when it is sensitive to context and the diversity of decision types, decision processes, and constituencies (*robust evidence*, *high agreement*). Organizations bridging science and decision making, including climate services, play an important role in the communication, transfer, and development of climate-related knowledge, including translation, engagement, and knowledge exchange (*medium evidence*, *high agreement*). [2.1 to 2.4, 8.4, 14.4, 16.2, 16.3, 16.5, 21.2, 21.3, 21.5, 22.4, Box 9-4]

Integration of adaptation into planning and decision making can promote synergies with development and disaster risk reduction (*high confidence*). Such mainstreaming embeds climate-sensitive thinking in existing and new institutions and organizations. Adaptation can generate larger benefits when connected with development activities and disaster risk reduction (*medium confidence*). [8.3, 9.3, 14.2, 14.6, 15.3, 15.4, 17.2, 20.2, 20.3, 22.4, 24.5, 29.6, Box CC-UR]

Existing and emerging economic instruments can foster adaptation by providing incentives for anticipating and reducing impacts (*medium confidence*). Instruments include public–private finance partnerships, loans, payments for environmental services, improved resource pricing, charges and subsidies, norms and regulations, and risk sharing and transfer mechanisms. Risk financing mechanisms in the public and private sector, such as insurance and risk pools, can contribute to increasing resilience, but without attention to major design challenges, they can also provide disincentives, cause market failure, and decrease equity. Governments often play key roles as regulators, providers, or insurers of last resort. [10.7, 10.9, 13.3, 17.4, 17.5, Box 25-7]

Constraints can interact to impede adaptation planning and implementation (*high confidence*). Common constraints on implementation arise from the following: limited financial and human resources; limited integration or coordination of governance; uncertainties about projected impacts; different perceptions of risks; competing values; absence of key adaptation leaders and advocates; and limited tools to monitor adaptation effectiveness. Another constraint includes insufficient research, monitoring, and observation and the finance to maintain them. Underestimating the complexity of adaptation as a social process can create unrealistic expectations about achieving intended adaptation outcomes. [3.6, 4.4, 5.5, 8.4, 9.4, 13.2, 13.3, 14.2, 14.5, 15.2, 15.3, 15.5, 16.2, 16.3, 16.5, 17.2, 17.3, 22.4, 23.7, 24.5, 25.4, 25.10, 26.8, 26.9, 30.6, Table 16-3, Boxes 16-1 and 16-3]

Poor planning, overemphasizing short-term outcomes, or failing to sufficiently anticipate consequences can result in maladaptation (*medium evidence*, *high agreement*). Maladaptation can increase the vulnerability or exposure of the target group in the future, or the vulnerability of other people, places, or sectors. Narrow focus on quantifiable costs and benefits can bias decisions against the poor, against ecosystems, and against those in the future whose values can be excluded or are understated. Some near-term responses to increasing risks related to climate change may also limit future choices. For example, enhanced protection of exposed assets can lock in dependence on further protection measures. [5.5, 8.4, 14.6, 15.5, 16.3, 17.2, 17.3, 20.2, 22.4, 24.4, 25.10, 26.8, Table 14-4, Box 25-1]

Limited evidence indicates a gap between global adaptation needs and funds available for adaptation (*medium confidence*). There is a need for a better assessment of global adaptation costs, funding, and investment. Studies estimating the global cost of adaptation are characterized by shortcomings in data, methods, and coverage (*high confidence*). [14.2, 17.4, Tables 17-2 and 17-3]

C-2. Climate-resilient Pathways and Transformation

Climate-resilient pathways are sustainable-development trajectories that combine adaptation and mitigation to reduce climate change and its impacts. They include iterative processes to ensure that effective risk management can be implemented and sustained. See Figure TS.13. [2.5, 20.3, 20.4]

Prospects for climate-resilient pathways for sustainable development are related fundamentally to what the world accomplishes with climate-change mitigation (*high confidence*). Since mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades. Delaying mitigation actions may reduce options for climate-resilient pathways in the future. [1.1, 19.7, 20.2, 20.3, 20.6, Figure 1-5]

Greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits (*high confidence*). See Box TS.8. Limits to adaptation occur when adaptive actions to avoid intolerable risks for an actor's objectives or for the needs of a system are not possible or are not currently available. Value-based judgments

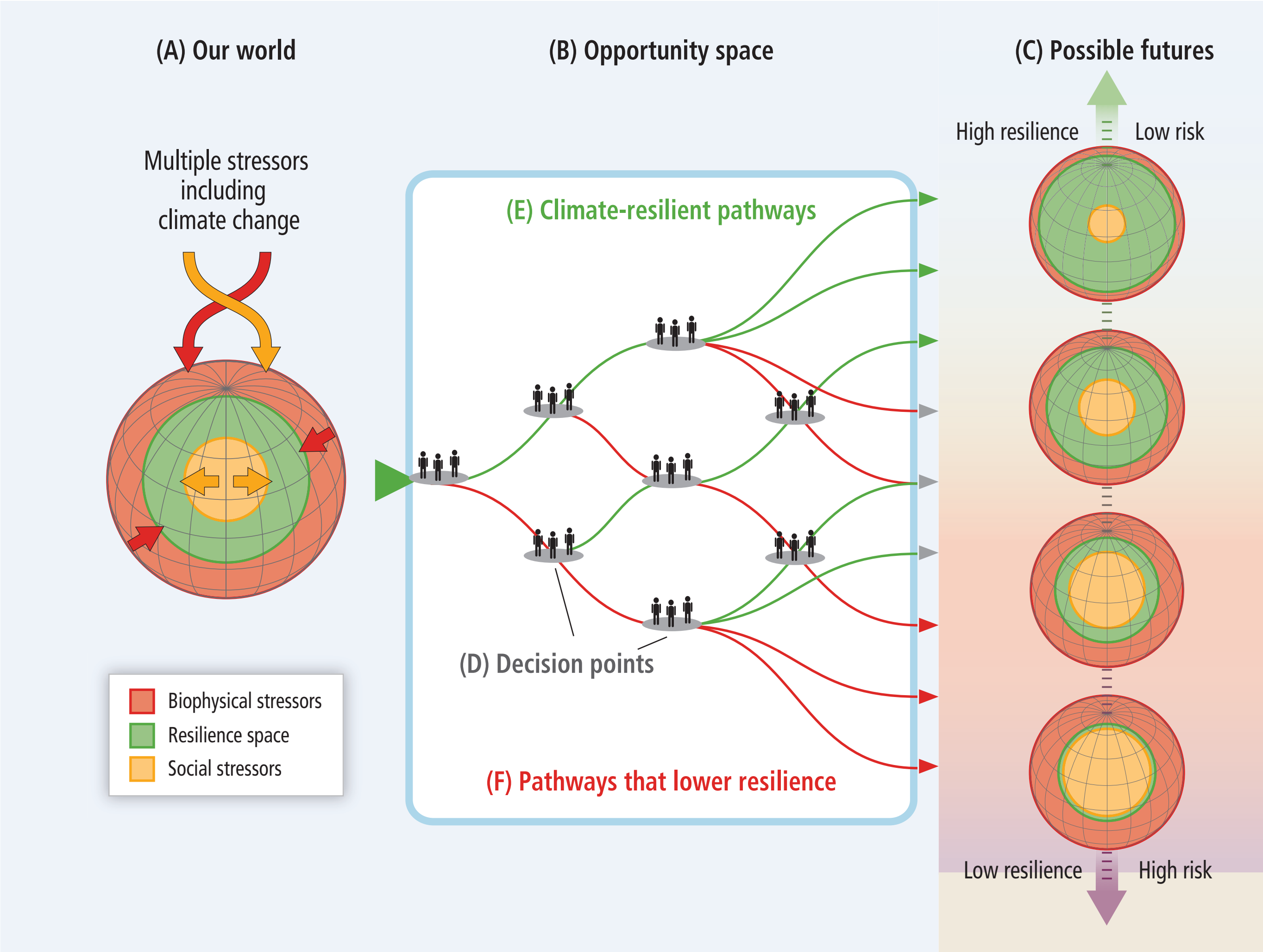


Figure TS.13 | Opportunity space and climate-resilient pathways. (A) Our world [Sections A-1 and B-1] is threatened by multiple stressors that impinge on resilience from many directions, represented here simply as biophysical and social stressors. Stressors include climate change, climate variability, land-use change, degradation of ecosystems, poverty and inequality, and cultural factors. (B) Opportunity space [Sections A-2, A-3, B-2, C-1, and C-2] refers to decision points and pathways that lead to a range of (C) possible futures [Sections C and B-3] with differing levels of resilience and risk. (D) Decision points result in actions or failures-to-act throughout the opportunity space, and together they constitute the process of managing or failing to manage risks related to climate change. (E) Climate-resilient pathways (in green) within the opportunity space lead to a more resilient world through adaptive learning, increasing scientific knowledge, effective adaptation and mitigation measures, and other choices that reduce risks. (F) Pathways that lower resilience (in red) can involve insufficient mitigation, maladaptation, failure to learn and use knowledge, and other actions that lower resilience; and they can be irreversible in terms of possible futures. [Figure 1-5]

of what constitutes an intolerable risk may differ. Limits to adaptation emerge from the interaction among climate change and biophysical and/or socioeconomic constraints. Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if limits to adaptation are exceeded. In some parts of the world, insufficient responses to emerging impacts are already eroding the basis for sustainable development. [1.1, 11.8, 13.4, 16.2 to 16.7, 17.2, 20.2, 20.3, 20.5, 20.6, 25.10, 26.5, Boxes 16-1, 16-3, and 16-4]

Transformations in economic, social, technological, and political decisions and actions can enable climate-resilient pathways (*high confidence*). Specific examples are presented in Table TS.7. See also Box TS.8. Strategies and actions can be pursued now that will move towards climate-resilient pathways for sustainable development, while at the same time helping to improve livelihoods, social and economic well-being, and responsible environmental management. Transformations in response to climate change may involve, for example, introduction of new technologies or practices, formation of new structures or systems of governance, or shifts in the types or locations of activities. The scale and magnitude of transformational adaptations depend on mitigation and on development processes. Transformational adaptation is an important consideration for decisions involving long life- or lead-times, and it can be a response to adaptation limits. At the national level, transformation is considered most effective when it reflects a country's own visions and approaches to achieving sustainable development in accordance with its national circumstances and priorities. Transformations to sustainability are considered to benefit from iterative learning, deliberative processes, and innovation. Societal debates about many aspects of transformation may place new and increased demands on governance structures. [1.1, 2.1, 2.5, 8.4, 14.1, 14.3, 16.2 to 16.7, 20.5, 22.4, 25.4, 25.10, Figure 1-5, Boxes 16-1 and 16-4]

Examples of Co-benefits, Synergies, and Trade-offs among Adaptation, Mitigation, and Sustainable Development

Significant co-benefits, synergies, and trade-offs exist between mitigation and adaptation and among different adaptation responses; interactions occur both within and across regions (*very high confidence*). Illustrative examples include the following.

- Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use, and biodiversity, but tools to understand and manage these interactions remain limited (*very high confidence*). See Box TS.9. Widespread transformation of terrestrial ecosystems in order to mitigate climate change, such as carbon sequestration through planting fast-growing tree species into ecosystems where they did not previously occur, or the conversion of previously uncultivated or non-degraded land to bioenergy plantations, can lead to negative impacts on ecosystems and biodiversity (*high confidence*). [3.7, 4.2 to 4.4, 22.6, 24.6, 25.7, 25.9, 27.3, Boxes 25-10 and CC-WE]
- Climate policies such as increasing energy supply from renewable resources, encouraging bioenergy crop cultivation, or facilitating payments under REDD+ will affect some rural areas both positively (e.g., increasing employment opportunities) and negatively (e.g., land use changes, increasing scarcity of natural capital) (*medium confidence*). These secondary impacts, and trade-offs between mitigation and adaptation in rural areas, have implications for governance, including benefits of promoting participation of rural stakeholders. Mitigation policies with social co-benefits expected in their design, such as CDM and REDD+, have had limited or no effect in terms of poverty alleviation and sustainable development

Box TS.8 | Adaptation Limits and Transformation

Adaptation can expand the capacity of natural and human systems to cope with a changing climate. Risk-based decision making can be used to assess potential limits to adaptation. Limits to adaptation occur when adaptive actions to avoid intolerable risks for an actor's objectives or for the needs of a system are not possible or are not currently available. Limits to adaptation are context-specific and closely linked to cultural norms and societal values. Value-based judgments of what constitutes an intolerable risk may differ among actors, but understandings of limits to adaptation can be informed by historical experiences, or by anticipation of impacts, vulnerability, and adaptation associated with different scenarios of climate change. The greater the magnitude or rate of climate change, the greater the likelihood that adaptation will encounter limits. [16.2 to 16.4, 20.5, 20.6, 22.4, 25.4, 25.10, Box 16-2]

Limits to adaptation may be influenced by the subjective values of societal actors, which can affect both the perceived need for adaptation and the perceived appropriateness of specific policies and measures. While limits imply that intolerable risks and the increased potential for losses and damages can no longer be avoided, the dynamics of social and ecological systems mean that there are both "soft" and "hard" limits to adaptation. For "soft" limits, there are opportunities in the future to alter limits and reduce risks, for example, through the emergence of new technologies or changes in laws, institutions, or values. In contrast, "hard" limits are those where there are no reasonable prospects for avoiding intolerable risks. Recent studies on tipping points, key vulnerabilities, and planetary boundaries provide some insights on the behavior of complex systems. [16.2 to 16.7, 25.10]

In cases where the limits to adaptation have been surpassed, losses and damage may increase and the objectives of some actors may no longer be achievable. There may be a need for transformational adaptation to change fundamental attributes of a system in response to actual or expected impacts of climate change. It may involve adaptations at a greater scale or intensity than previously experienced, adaptations that are new to a region or system, or adaptations that transform places or lead to a shift in the types or locations of activities. [16.2 to 16.4, 20.3, 20.5, 22.4, 25.10, Boxes 25-1 and 25-9]

The existence of limits to adaptation suggests transformational change may be a requirement for sustainable development in a changing climate—that is, not only for adapting to the impacts of climate change, but for altering the systems and structures, economic and social relations, and beliefs and behaviors that contribute to climate change and social vulnerability. However, just as there are ethical implications associated with some adaptation options, there are also legitimate concerns about the equity and ethical dimensions of transformation. Societal debates over risks from forced and reactive transformations as opposed to deliberate transitions to sustainability may place new and increased demands on governance structures at multiple levels to reconcile conflicting goals and visions for the future. [1.1, 16.2 to 16.7, 20.5, 25.10] (*medium confidence*). Mitigation efforts focused on land acquisition for biofuel production show preliminary negative impacts for the poor in many developing countries, and particularly for indigenous people and (women) smallholders. [9.3, 13.3, 22.6]

- Mangrove, seagrass, and salt marsh ecosystems offer important carbon storage and sequestration opportunities (*limited evidence*, *medium agreement*), in addition to ecosystem goods and services such as protection against coastal erosion and storm damage and maintenance of habitats for fisheries species. For ocean-related mitigation and adaptation in the context of anthropogenic ocean warming and acidification, international frameworks offer opportunities to solve problems collectively, for example, managing fisheries across national borders and responding to extreme events. [5.4, 25.6, 30.6, 30.7]

Table TS.8 | Illustrative examples of intra-regional interactions among adaptation, mitigation, and sustainable development.

Green infrastructure and green roofs	
Objectives	Storm water management, adaptation to increasing temperatures, reduced energy use, urban regeneration
Relevant sectors	Infrastructure, energy use, water management
Overview	Benefits of green infrastructure and roofs can include reduction of storm water runoff and the urban heat island effect, improved energy performance of buildings, reduced noise and air pollution, health improvements, better amenity value, increased property values, improved biodiversity, and inward investment. Trade-offs can result between higher urban density to improve energy efficiency and open space for green infrastructure. [8.3.3, 11.7.4, 23.7.4, 24.6, Tables 11-3 and 25-5]
Examples with interactions	**London:** The Green Grid for East London seeks to create interlinked and multi-purpose open spaces to support regeneration of the area. It aims to connect people and places, to absorb and store water, to cool the vicinity, and to provide a diverse mosaic of habitats for wildlife. [8.3.3] **New York:** In preparation for more intense storms, New York is using green infrastructure to capture rainwater before it can flood the combined sewer system, implementing green roofs, and elevating boilers and other equipment above ground. [8.3.3, 26.3.3, 26.8.4] **Singapore:** Singapore has used several anticipatory plans and projects to enhance green infrastructure, including its Streetscape Greenery Master Plan, constructed wetlands or drains, and community gardens. Under its Skyrise Greenery project, Singapore has provided subsidies and handbooks for rooftop and wall greening initiatives. [8.3.3] **Durban:** Ecosystem-based adaptation is part of Durban's climate change adaptation strategy. The approach seeks a more detailed understanding of the ecology of indigenous ecosystems and ways in which biodiversity and ecosystem services can reduce vulnerability of ecosystems and people. Examples include the Community Reforestation Programme, in which communities produce indigenous seedlings used in the planting and managing of restored forest areas. Development of ecosystem-based adaptation in Durban has demonstrated needs for local knowledge and data and the benefits of enhancing existing protected areas, land-use practices, and local initiatives contributing to jobs, business, and skill development. [8.3.3, Box 8-2]
Water management	
Primary objective	Water resource management given multiple stressors in a changing climate
Relevant sectors	Water use, energy production and use, biodiversity, carbon sequestration, biofuel production, food production
Overview	Water management in the context of climate change can encompass ecosystem-based approaches (e.g., watershed management or restoration, flood regulation services, and reduction of erosion or siltation), supply-side approaches (e.g., dams, reservoirs, groundwater pumping and recharge, and water capture), and demand-side approaches (e.g., increased use efficiency through water recycling, infrastructure upgrades, water-sensitive design, or more efficient allocation). Water may require significant amounts of energy for lifting, transport, distribution, and treatment. [3.7.2, 26.3, Tables 9-8 and 25-5, Boxes CC-EA and CC-WE]
Examples with interactions	**New York:** New York has a well-established program to protect and enhance its water supply through watershed protection. The Watershed Protection Program includes city ownership of land that remains undeveloped and coordination with landowners and communities to balance water-quality protection, local economic development, and improved wastewater treatment. The city government indicates it is the most cost-effective choice for New York given the costs and environmental impacts of a filtration plant. [8.3.3, Box 26-3] **Cape Town:** Facing challenges in ensuring future supplies, Cape Town responded by commissioning water management studies, which identified the need to incorporate climate change, as well as population and economic growth, in planning. During the 2005 drought, local authorities increased water tariffs to promote efficient water usage. Additional measures may include water restrictions, reuse of gray water, consumer education, or technological solutions such as low-flow systems or dual flush toilets. [8.3.3] **Capital cities in Australia:** Many Australian capital cities are reducing reliance on catchment runoff and groundwater—water resources most sensitive to climate change and drought—and are diversifying supplies through desalination plants, water reuse including sewage and storm water recycling, and integrated water cycle management that considers climate change impacts. Demand is being reduced through water conservation and water-sensitive urban design and, during severe shortfalls, through implementation of restrictions. The water augmentation program in Melbourne includes a desalination plant. Trade-offs beyond energy intensiveness have been noted, such as damage to sites significant to aboriginal communities and higher water costs that will disproportionately affect poorer households. [14.6.2, Tables 25-6 and 25-7, Box 25-2]
Payment for environmental services and green fiscal policies	
Primary objective	Management incorporating the costs of environmental externalities and the benefits of ecosystem services
Relevant sectors	Biodiversity, ecosystem services
Overview	Payment for environmental services (PES) is a market-based approach that aims to protect natural areas, and associated livelihoods and environmental services, by developing financial incentives for preservation. Mitigation-focused PES schemes are common, and there is emerging evidence of adaptation-focused PES schemes. Successful PES approaches can be difficult to design for services that are hard to define or quantify. [17.5.2, 27.6.2]
Examples with interactions	**Central and South America:** A variety of PES schemes have been implemented in Central and South America. For example, national-level programs have operated in Costa Rica and Guatemala since 1997 and in Ecuador since 2008. Examples to date have shown that PES can finance conservation, ecosystem restoration and reforestation, better land-use practices, mitigation, and more recently adaptation. Uniform payments for beneficiaries can be inefficient if, for example, recipients that promote greater environmental gains receive only the prevailing payment. [17.5.2, 27.3.2, 27.6.2, Table 27-8] **Brazil:** Municipal funding in Brazil tied to ecosystem-management quality is a form of revenue transfer important to funding local adaptation actions. State governments collect a value-added tax redistributed among municipalities, and some states allocate revenues in part based on municipality area set aside for protection. This mechanism has helped improve environmental management and increased creation of protected areas. It benefits relations between protected areas and surrounding inhabitants, as the areas can be perceived as opportunities for revenue generation rather than as obstacles to development. The approach builds on existing institutions and administrative procedures and thus has low transaction costs. [8.4.3, Box 8-4]

Continued next page →

Table TS.8 (continued)

Renewable energy	
Primary objective	Renewable energy production and reduction of emissions
Relevant sectors	Biodiversity, agriculture, food security
Overview	Renewable energy production can require significant land areas and water resources, creating the potential for both positive and negative interactions between mitigation policies and land management. [4.4.4, 13.3.1, 19.3.2, 19.4.1, Box CC-WE]
Examples with interactions	**Central and South America:** Renewable resources, especially hydroelectric power and biofuels, account for substantial fractions of energy production in countries such as Brazil. Where bioenergy crops compete for land with food crops, substantial trade-offs can exist. Land-use change to produce bioenergy can affect food crops, biodiversity, and ecosystem services. Lignocellulosic feedstocks, such as sugarcane second-generation technologies, do not compete with food. [19.3.2, 27.3.6, 27.6.1, Table 27-6] **Australia and New Zealand:** Mandatory renewable energy targets and incentives to increase carbon storage support increased biofuel production and increased biological carbon sequestration, with impacts on biodiversity depending on implementation. Benefits can include reduced erosion, additional habitat, and enhanced connectivity, with risks or lost opportunities associated with large-scale monocultures especially if replacing more diverse landscapes. Large-scale land cover changes can affect catchment yields and regional climate in complex ways. New crops such as oil mallees or other eucalypts may provide multiple benefits, especially in marginal areas, displacing fossil fuels or sequestering carbon, generating income for landholders (essential oils, charcoal, bio-char, biofuels), and providing ecosystem services. [Table 25-7, Box 25-10]
Disaster risk reduction and adaptation to climate extremes	
Primary objective	Increasing resilience to extreme weather events in a changing climate
Relevant sectors	Infrastructure, energy use, spatial planning
Overview	Synergies and tradeoffs among sustainable development, adaptation, and mitigation occur in preparing for and responding to climate extremes and disasters. [13.2 to 13.4, 20.3, 20.4]
Examples with interactions	**Philippines:** The Homeless People's Federation of the Philippines developed responses following disasters, including community-rooted data gathering (e.g., assessing destruction and victims' immediate needs); trust and contact building; savings support; community-organization registration; and identification of needed interventions (e.g., building-materials loans). Community surveys mapped inhabitants especially at risk in informal settlements, raising risk-awareness among the inhabitants and increasing community engagement in planning risk reduction and early warning systems. [8.3.2, 8.4.2] **London:** Within London, built form and other dwelling characteristics can have a stronger influence on indoor temperatures during heat waves than the urban heat island effect, and utilizing shade, thermal mass, ventilation control, and other passive-design features are effective adaptation options. Passive housing designs enhance natural ventilation and improve insulation, while also reducing household emissions. For example, in London the Beddington Zero Energy Development was designed to reduce or eliminate energy demand for heating, cooling, and ventilation for much of the year. [8.3.3, 11.7.4] **United States:** In the United States, post-disaster funds for loss reduction are added to funds provided for disaster recovery. They can be used, for instance, to buy out properties that have experienced repetitive flood losses and relocate residents to safer locations, to elevate structures, to assist communities with purchasing property and altering land-use patterns in flood-prone areas, and to undertake other activities designed to lessen the impacts of future disasters. [14.3.3]

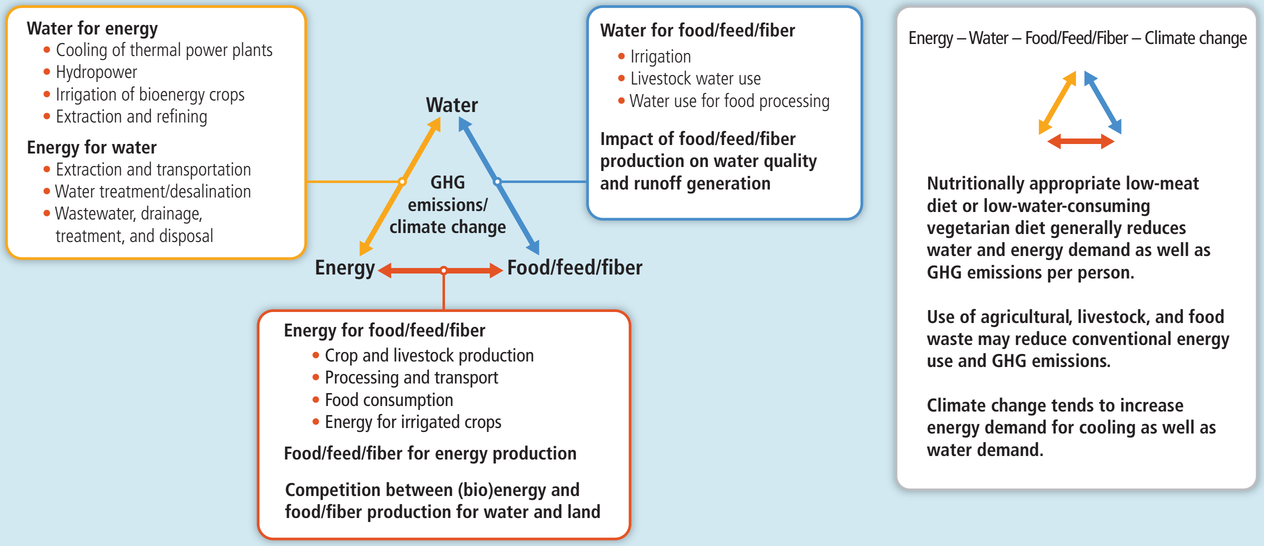
- Geoengineering approaches involving manipulation of the ocean to ameliorate climate change (such as nutrient fertilization, binding of CO_2 by enhanced alkalinity, or direct CO_2 injection into the deep ocean) have very large environmental and associated socioeconomic consequences (*high confidence*). Alternative methods focusing on solar radiation management (SRM) leave ocean acidification unabated as they cannot mitigate rising atmospheric CO_2 emissions. [6.4]
- Some agricultural practices can reduce emissions and also increase resilience of crops to temperature and rainfall variability (*high confidence*). [23.8, Table 25-7]
- Many solutions for reducing energy and water consumption in urban areas with co-benefits for climate change adaptation (e.g., greening cities and recycling water) are already being implemented (*high confidence*). Transport systems promoting active transport and reduced motorized-vehicle use can improve air quality and increase physical activity (*medium confidence*). [11.9, 23.8, 24.4, 26.3, 26.8, Boxes 25-2 and 25-9]
- Improved energy efficiency and cleaner energy sources can lead to reduced emissions of health-damaging climate-altering air pollutants (*very high confidence*). [11.9, 23.8]
- In Africa, experience in implementing integrated adaptation–mitigation responses that leverage developmental benefits encompasses some participation of farmers and local communities in carbon offset systems and increased use of agroforestry and farmer-assisted tree regeneration (*high confidence*). [22.4, 22.6]
- In Asia, development of sustainable cities with fewer fossil-fuel-driven vehicles and with more trees and greenery would have a number of co-benefits, including improved public health (*high confidence*). [24.4 to 24.7]
- In Australasia, transboundary effects from climate change impacts and responses outside Australasia have the potential to outweigh some of the direct impacts within the region, particularly economic impacts on trade-intensive sectors such as agriculture (*medium confidence*) and tourism (*limited evidence*, *high agreement*), but they remain among the least-explored issues. [25.7, 25.9, Box 25-10]
- In North America, policies addressing local concerns (e.g., air pollution, housing for the poor, declines in agricultural production) can be adapted at low or no cost to fulfill adaptation, mitigation, and sustainability goals (*medium confidence*). [26.9]
- In Central and South America, biomass-based renewable energy can impact land use change and deforestation, and could be affected by climate change (*medium confidence*). The expansion of sugarcane, soy, and oil palm may have some effect on land use, leading to deforestation in parts of the Amazon and Central America, among other sub-regions, and to loss of employment in some countries. [27.3]
- For small islands, energy supply and use, tourism infrastructure and activities, and coastal wetlands offer opportunities for adaptation–mitigation synergies (*medium confidence*). [29.6 to 29.8]

Table TS.8 provides further specific examples of interactions among adaptation, mitigation, and sustainable development to complement the assessment findings above.

TS

Box TS.9 | The Water–Energy–Food Nexus

Water, energy, and food/feed/fiber are linked through numerous interactive pathways affected by a changing climate (Box TS.9 Figure 1). [Box CC-WE] The depth and intensity of those linkages vary enormously among countries, regions, and production systems. Many energy sources require significant amounts of water and produce a large quantity of wastewater that requires energy for treatment. [3.7, 7.3, 10.2, 10.3, 22.3, 25.7, Box CC-WE] Food production, refrigeration, transport, and processing also require both energy and water. A major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water, and the sensitivity of precipitation, temperature, and crop yields to climate change (*robust evidence*, *high agreement*). [7.3, Boxes 25-10 and CC-WE]



Box TS.9 Figure 1 | The water–energy–food nexus as related to climate change, with implications for both adaptation and mitigation strategies. [Figure WE-1, Box CC-WE]

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (*robust evidence*, *high agreement*). [10.2, 10.3, 25.7, Box CC-WE] Water is required for mining, processing, and residue disposal of fossil fuels or their byproducts. [25.7] Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country. [Box CC-WE] Future water requirements will depend on electric demand growth, the portfolio of generation technologies, and water management options (*medium evidence*, *high agreement*). Future water availability for energy production will change due to climate change (*robust evidence*, *high agreement*). [3.4, 3.5, Box CC-WE]

Energy is also required to supply and treat water. Water may require significant amounts of energy for lifting (especially as aquifers continue to be depleted), transport, and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. [Table 25-7, Box 25-2] Energy intensities per cubic meter of water vary by about a factor of 10 among different sources, for example, locally produced potable water from ground/surface water sources versus desalinated seawater. [Boxes 25-2 and CC-WE] Groundwater is generally more energy intensive than surface water. [Box CC-WE]

Linkages among water, energy, food/feed/fiber, and climate are strongly related to land use and management, such as afforestation, which can affect water as well as other ecosystem services, climate, and water cycles (*robust evidence*, *high agreement*). Land degradation often reduces efficiency of water and energy use (e.g., resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security. On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat, but may reduce renewable water resources. [3.7, 4.4, Boxes 25-10 and CC-WE]

Consideration of the interlinkages of energy, food/feed/fiber, water, land use, and climate change has implications for security of supplies of energy, food, and water; adaptation and mitigation pathways; air pollution reduction; and health and economic impacts. This nexus is increasingly recognized as critical to effective climate-resilient-pathway decision making (*medium evidence*, *high agreement*), although tools to support local- and regional-scale assessments and decision support remain very limited.

Working Group II Frequently Asked Questions

These FAQs provide an entry point to the approach and scientific findings of the Working Group II contribution to the Fifth Assessment Report. For summary of the scientific findings, see the Summary for Policymakers (SPM) and Technical Summary (TS). These FAQs, presented in clear and accessible language, do not reflect formal assessment of the degree of certainty in conclusions, and they do not include calibrated uncertainty language presented in the SPM, TS, and underlying chapters. The sources of the relevant assessment in the report are noted by chapter numbers in square brackets.

FAQ 1: Are risks of climate change mostly due to changes in extremes, changes in average climate, or both?

[Chapters 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 18, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30; TS]

People and ecosystems across the world experience climate in many different ways, but weather and climate extremes strongly influence losses and disruptions. Average climate conditions are important. They provide a starting point for understanding what grows where and for informing decisions about tourist destinations, other business opportunities, and crops to plant. But the impacts of a change in average conditions often occur as a result of changes in the frequency, intensity, or duration of extreme weather and climate events. It is the extremes that place excessive and often unexpected demands on systems poorly equipped to deal with those extremes. For example, wet conditions lead to flooding when storm drains and other infrastructure for handling excess water are overwhelmed. Buildings fail when wind speeds exceed design standards. For many kinds of disruption, from crop failure caused by drought to sickness and death from heat waves, the main risks are in the extremes, with changes in average conditions representing a climate with altered timing, intensity, and types of extremes.

FAQ 2: How much can we say about what society will be like in the future, in order to plan for climate change impacts?

[Chapters 1, 2, 14, 15, 16, 17, 20, and 21; TS]

Overall characteristics of societies and economies, such as population size, economic activity, and land use, are highly dynamic. On the scale of just 1 or 2 decades, and sometimes in less time than that, technological revolutions, political movements, or singular events can shape the course of history in unpredictable ways. To understand potential impacts of climate change for societies and ecosystems, scientists use scenarios to explore implications of a range of possible futures. Scenarios are not predictions of what will happen, but they can be useful tools for researching a wide range of "what if" questions about what the world might be like in the future. They can be used to study future emissions of greenhouse gases and climate change. They can also be used to explore the ways climate-change impacts depend on changes in society, such as economic or population growth or progress in controlling diseases. Scenarios of possible decisions and policies can be used to explore the solution space for reducing greenhouse gas emissions and preparing for a changing climate. Scenario analysis creates a foundation for understanding risks of climate change for people, ecosystems, and economies across a range of possible futures. It provides important tools for smart decision making when both uncertainties and consequences are large.

FAQ 3: Why is climate change a particularly difficult challenge for managing risk?

[Chapters 1, 2, 16, 17, 19, 20, 21, and 25; TS]

Risk management is easier for nations, companies, and even individuals when the likelihood and consequences of possible events are readily understood. Risk management becomes much more challenging when the stakes are higher or when uncertainty is greater. As the WGII AR5 demonstrates, we know a great deal about the impacts of climate change that have already occurred, and we understand a great deal about expected impacts in the future. But many uncertainties remain, and will persist. In particular, future greenhouse gas emissions depend on societal choices, policies, and technology advancements not yet made, and climate-change impacts depend on both the amount of climate change that occurs and the effectiveness of development in reducing exposure and vulnerability. The real challenge of dealing effectively with climate change is recognizing the value of wise and timely decisions in a setting where complete knowledge is impossible. This is the essence of risk management.

FAQ 4: What are the timeframes for mitigation and adaptation benefits?

[Chapters 1, 2, 16, 19, 20, and 21; TS]

Adaptation can reduce damage from impacts that cannot be avoided. Mitigation strategies can decrease the amount of climate change that occurs, as summarized in the WGIII AR5. But the consequences of investments in mitigation emerge over time. The constraints of existing infrastructure, limited deployment of many clean technologies, and the legitimate aspirations for economic growth around the world all tend to slow the deviation from established trends in greenhouse gas emissions. Over the next few decades, the climate change we experience will be determined primarily by the combination of past actions and current trends. The near-term is thus an era where short-term risk reduction comes from adapting to the changes already underway. Investments in mitigation during both the near-term and the longer-term do, however, have substantial leverage on the magnitude of climate change in the latter decades of the century, making the second half of the 21st century and beyond an era of climate options. Adaptation will still be important during the era of climate options, but with opportunities and needs that will depend on many aspects of climate change and development policy, both in the near term and in the long term.

FAQ 5: Can science identify thresholds beyond which climate change is dangerous?

[Chapters 1, 2, 4, 5, 6, 16, 17, 18, 19, 20, and 25; TS]

Human activities are changing the climate. Climate-change impacts are already widespread and consequential. But while science can quantify climate change risks in a technical sense, based on the probability, magnitude, and nature of the potential consequences of climate change, determining what is dangerous is ultimately a judgment that depends on values and objectives. For example, individuals will value the present versus the future differently and will bring personal worldviews on the importance of assets like biodiversity, culture, and aesthetics. Values also influence judgments about the relative importance of global economic growth versus assuring the well-being of the most vulnerable among us. Judgments about dangerousness can depend on the extent to which one's livelihood, community, and family are directly exposed and vulnerable to climate change. An individual or community displaced by climate change might legitimately consider that specific impact dangerous, even though that single impact might not cross the global threshold of dangerousness. Scientific assessment of risk can provide an important starting point for such value judgments about the danger of climate change.

FAQ 6: Are we seeing impacts of recent climate change?

[Chapters 3, 4, 5, 6, 7, 11, 13, 18, 22, 23, 24, 25, 26, 27, 28, 29, and 30; SPM]

Yes, there is strong evidence of impacts of recent observed climate change on physical, biological, and human systems. Many regions have experienced warming trends and more frequent high-temperature extremes. Rising temperatures are associated with decreased snowpack, and many ecosystems are experiencing climate-induced shifts in the activity, range, or abundance of the species that inhabit them. Oceans are also displaying changes in physical and chemical properties that, in turn, are affecting coastal and marine ecosystems such as coral reefs, and other oceanic organisms such as mollusks, crustaceans, fishes, and zooplankton. Crop production and fishery stocks are sensitive to changes in temperature. Climate change impacts are leading to shifts in crop yields, decreasing yields overall and sometimes increasing them in temperate and higher latitudes, and catch potential of fisheries is increasing in some regions but decreasing in others. Some indigenous communities are changing seasonal migration and hunting patterns to adapt to changes in temperature.

FAQ 7: Are the future impacts of climate change only negative? Might there be positive impacts as well?

[Chapters 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 19, 22, 23, 24, 25, 26, 27, and 30]

Overall, the report identifies many more negative impacts than positive impacts projected for the future, especially for high magnitudes and rates of climate change. Climate change will, however, have different impacts on people around the world and those effects will vary not only by region but over time, depending on the rate and magnitude of climate change. For example, many countries will face increased challenges for economic development, increased risks from some diseases, or degraded ecosystems, but some countries will probably have increased opportunities for economic development, reduced instances of some diseases, or expanded areas of productive land. Crop yield changes will vary with geography and by latitude. Patterns of potential catch for fisheries are changing globally as well, with both positive and negative consequences. Availability of resources such as usable water will also depend on changing rates of precipitation, with decreased availability in many places but possible increases in runoff and groundwater recharge in some regions like the high latitudes and wet tropics.

FAQ 8: What communities are most vulnerable to the impacts of climate change?

[Chapters 8, 9, 12, 13, 19, 22, 23, 26, 27, 29, and Box CC-GC]

Every society is vulnerable to the impacts of climate change, but the nature of that vulnerability varies across regions and communities, over time, and depends on unique socioeconomic and other conditions. Poorer communities tend to be more vulnerable to loss of health and life, while wealthier communities usually have more economic assets at risk. Regions affected by violence or governance failure can be particularly vulnerable to climate change impacts. Development challenges, such as gender inequality and low levels of education, and other differences among communities in age, race and ethnicity, socioeconomic status, and governance can influence vulnerability to climate change impacts in complex ways.

FAQ 9: Does climate change cause violent conflicts?

[Chapters 12, 19]

Some factors that increase risks from violent conflicts and civil wars are sensitive to climate change. For example, there is growing evidence that factors like low per capita incomes, economic contraction, and inconsistent state institutions are associated with the incidence of civil wars, and also seem to be sensitive to climate change. Climate-change policies, particularly those associated with changing rights to resources, can also increase risks from violent conflict. While statistical studies document a relationship between climate variability and conflict, there remains much disagreement about whether climate change directly causes violent conflicts.

FAQ 10: How are adaptation, mitigation, and sustainable development connected?

[Chapters 1, 2, 8, 9, 10, 11, 13, 17, 20, 22, 23, 24, 25, 26, 27, and 29]

Mitigation has the potential to reduce climate change impacts, and adaptation can reduce the damage of those impacts. Together, both approaches can contribute to the development of societies that are more resilient to the threat of climate change and therefore more sustainable. Studies indicate that interactions between adaptation and mitigation responses have both potential synergies and tradeoffs that vary according to context. Adaptation responses may increase greenhouse gas emissions (e.g., increased fossil-based air conditioning in response to higher temperatures), and mitigation may impede adaptation (e.g., increased use of land for bioenergy crop production negatively impacting ecosystems). There are growing examples of co-benefits of mitigation and development policies, like those which can potentially reduce local emissions of health-damaging and climate-altering air pollutants from energy systems. It is clear that adaptation, mitigation, and sustainable development will be connected in the future.

FAQ 11: Why is it difficult to be sure of the role of climate change in observed effects on people and ecosystems?

[Chapter 3, 4, 5, 6, 7, 11, 12, 13, 18, 22, 23, 24, 25, 26, 27, 28, 29, and 30]

Climate change is one of many factors impacting the Earth's complex human societies and natural ecosystems. In some cases the effect of climate change has a unique pattern in space or time, providing a fingerprint for identification. In others, potential effects of climate change are thoroughly mixed with effects of land use change, economic development, changes in technology, or other processes. Trends in human activities, health, and society often have many simultaneous causes, making it especially challenging to isolate the role of climate change.

Much climate-related damage results from extreme weather events and could be affected by changes in the frequency and intensity of these events due to climate change. The most damaging events are rare, and the level of damage depends on context. It can therefore be challenging to build statistical confidence in observed trends, especially over short time periods. Despite this, many climate change impacts on the physical environment and ecosystems have been identified, and increasing numbers of impacts have been found in human systems as well.

Cross-Chapter Boxes

CR

Coral Reefs

Jean-Pierre Gattuso (France), Ove Hoegh-Guldberg (Australia), Hans-Otto Pörtner (Germany)

Coral reefs are shallow-water ecosystems that consist of reefs made of calcium carbonate which is mostly secreted by reef-building corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics, housing high levels of biological diversity as well as providing key ecosystem goods and services such as habitat for fisheries, coastal protection, and appealing environments for tourism (Wild et al., 2011). About 275 million people live within 30 km of a coral reef (Burke et al., 2011) and derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011), including provisioning (food, livelihoods, construction material, medicine), regulating (shoreline protection, water quality), supporting (primary production, nutrient cycling), and cultural (religion, tourism) services. This is especially true for the many coastal and small island nations in the world's tropical regions (Section 29.3.3.1).

Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*; Sections 5.4.2.4, 6.3.1, 6.3.2, 6.3.5, 25.6.2, and 30.5), and more than half of the world's reefs are under medium or high risk of degradation (Burke et al., 2011). Most human-induced disturbances to coral reefs were local until the early 1980s (e.g., unsustainable coastal development, pollution, nutrient enrichment, and overfishing) when disturbances from ocean warming (principally mass coral bleaching and mortality) began to become widespread (Glynn, 1984). Concern about the impact of ocean acidification on coral reefs developed over the same period, primarily over the implications of ocean acidification for the building and maintenance of the calcium carbonate reef framework (Box CC-OA).

A wide range of climatic and non-climatic drivers affect corals and coral reefs and negative impacts have already been observed (Sections 5.4.2.4, 6.3.1, 6.3.2, 25.6.2.1, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae, which live in the coral tissues and play a key role in supplying the coral host with energy (see Section 6.3.1. for physiological details and Section 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies (*high confidence*), is the most widespread and conspicuous impact of climate change (Figure CR-1A and B, Figure 5-3; Sections 5.4.2.4, 6.3.1, 6.3.5, 25.6.2.1, 30.5, and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997–1998 was unmatched in the period 1903–1999 (Lough, 2000). Ocean acidification reduces biodiversity (Figure CR-1C and D) and the calcification rate of corals (*high confidence*; Sections 5.4.2.4, 6.3.2, 6.3.5) while at the same time increasing the rate of dissolution of the reef framework (*medium confidence*; Section 5.2.2.4) through stimulation of biological erosion and chemical dissolution. Taken together, these changes will tip the calcium carbonate balance of coral reefs toward net dissolution (*medium confidence*; Section 5.4.2.4).

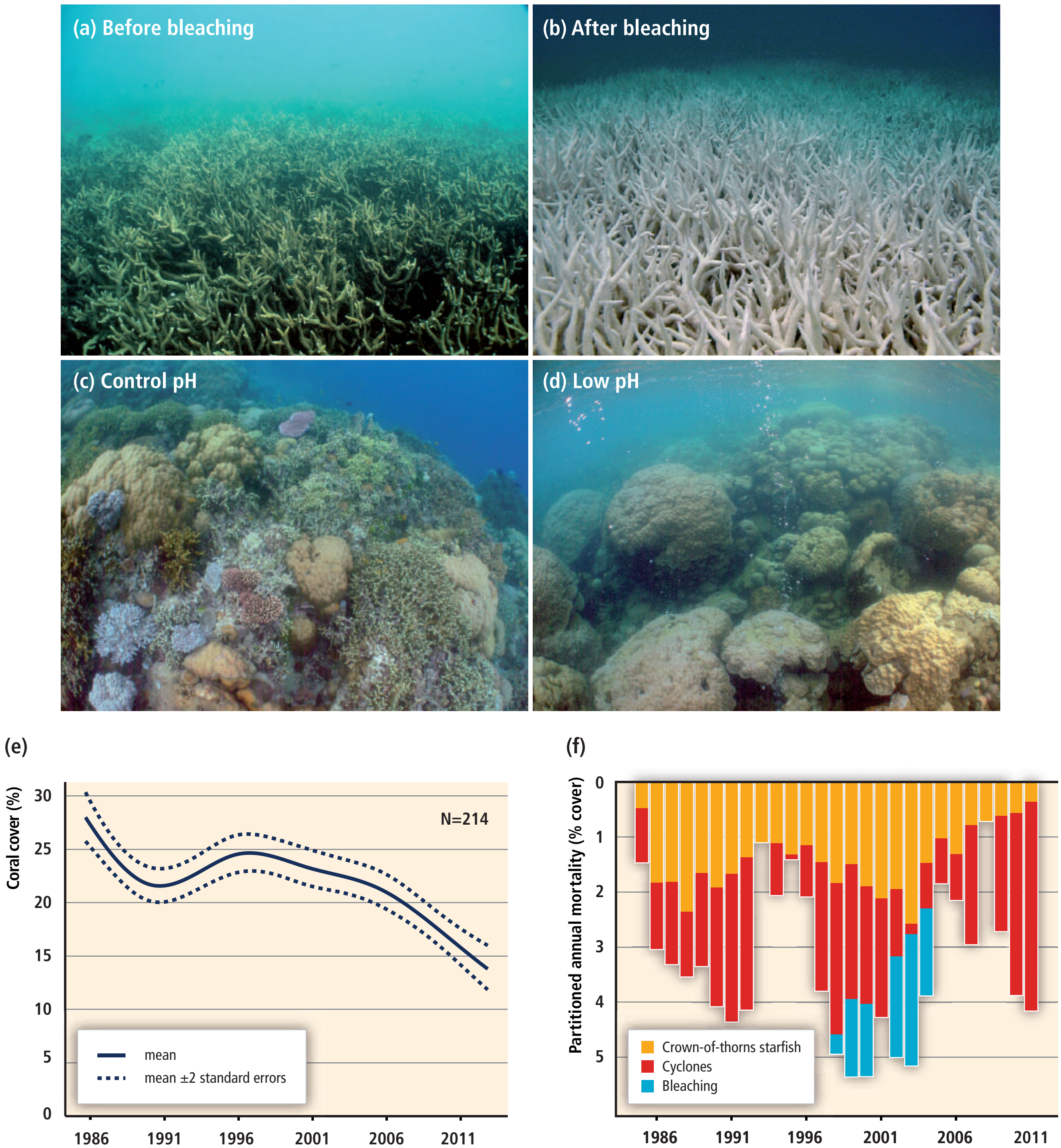


Figure CR-1 | (a, b) The same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Approximately 95% of the coral community was severely bleached in 2002 (Elvidge et al., 2004). Corals experience increasing mortality as the intensity of a heating event increases. A few coral species show the ability to shuffle symbiotic communities of dinoflagellates and appear to be more tolerant of warmer conditions (Berkelmans and van Oppen, 2006; Jones et al., 2008). (c, d) Three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius et al., 2011), including reduced coral diversity (–39%), severely reduced structural complexity (–67%), lower density of young corals (–66%), and fewer crustose coralline algae (–85%). At high CO_2 sites (d; median pH_T ~7.8, where pH_T is pH on the total scale), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (c; median pH_T ~8.0). Reef development ceases at pH_T values below 7.7. (e) Temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N=number of reefs, De'ath et al., 2012). (f) Composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). (Photo credit: R. Berkelmans (a and b) and K. Fabricius (c and d).)

Ocean warming and acidification have synergistic effects in several reef-builders (Section 5.2.4.2, 6.3.5). Taken together, these changes will erode habitats for reef-based fisheries, increase the exposure of coastlines to waves and storms, as well as degrading environmental features important to industries such as tourism (*high confidence*; Section 6.4.1.3, 25.6.2, 30.5).

A growing number of studies have reported regional scale changes in coral calcification and mortality that are consistent with the scale and impact of ocean warming and acidification when compared to local factors such as declining water quality and overfishing (Hoegh-Guldberg et al., 2007). The abundance of reef building corals is in rapid decline in many Pacific and Southeast Asian regions (*very high confidence*, 1 to 2% per year for 1968–2004; Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by more than 80% on many Caribbean reefs (1977–2001; Gardner et al., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators, and thermal stress-related coral bleaching and mortality have led to a decline in coral cover on the Great Barrier Reef by about 51% between 1985 and 2012 (Figure CR-1E and F). Although less well documented, benthic invertebrates other than corals are also at risk (Przeslawski et al., 2008). Fish biodiversity is threatened by the permanent degradation of coral reefs, including in a marine reserve (Jones et al., 2004).

Future impacts of climate-related drivers (ocean warming, acidification, sea level rise as well as more intense tropical cyclones and rainfall events) will exacerbate the impacts of non-climate–related drivers (*high confidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9 to 60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation (next few decades) under the Representative Concentration Pathway (RCP)3-PD scenario (Frieler et al., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30 to 88%, 68% uncertainty range). If present-day corals have residual capacity to acclimate and/or adapt, half of the coral reefs may avoid high-frequency bleaching through 2100 (*limited evidence*, *limited agreement*; Logan et al., 2014). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

Damage to coral reefs has implications for several key regional services:

- *Resources*: Coral reefs account for 10 to 12% of the fish caught in tropical countries, and 20 to 25% of the fish caught by developing nations (Garcia and de Leiva Moreno, 2003). More than half (55%) of the 49 island countries considered by Newton et al. (2007) are already exploiting their coral reef fisheries in an unsustainable way and the production of coral reef fish in the Pacific is projected to decrease 20% by 2050 under the Special Report on Emission Scenarios (SRES) A2 emissions scenario (Bell et al., 2013).
- *Coastal protection*: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard et al., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification, and higher rates of dissolution and bioerosion due to ocean warming and acidification (Sections 5.4.2.4, 6.4.1, 30.5).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke et al., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).

Coral reefs make a modest contribution to the global gross domestic product (GDP) but their economic importance can be high at the country and regional scales (Pratchett et al., 2008). For example, tourism and fisheries represent 5% of the GDP of South Pacific islands (average for 2001–2011; Laurans et al., 2013). At the local scale, these two services provided in 2009–2011 at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans et al., 2013).

Isolated reefs can recover from major disturbance, and the benefits of their isolation from chronic anthropogenic pressures can outweigh the costs of limited connectivity (Gilmour et al., 2013). Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod et al., 2009). Although they are key conservation and management tools, they are unable to protect corals directly from thermal stress (Selig et al., 2012), suggesting that they need to be complemented with additional and alternative strategies (Rau et al., 2012; Billé et al., 2013). While MPA networks are a critical management tool, they should be established considering other forms of resource management (e.g., fishery catch limits and gear restrictions) and integrated ocean and coastal management to control land-based threats such as pollution and sedimentation. There is *medium confidence* that networks of highly protected areas nested within a broader management framework can contribute to preserving coral reefs under increasing human pressure at local and global scales (Salm et al., 2006). Locally, controlling the input of nutrients and sediment from land is an important complementary management strategy (Mcleod et al., 2009) because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann et al., 2013) and coastal pollutants enriched with fertilizers can increase acidification (Kelly et al., 2011). In the long term, limiting the amount of ocean warming and acidification is central to ensuring the viability of coral reefs and dependent communities (*high confidence*; Section 5.2.4.4, 30.5).

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EA

Ecosystem-Based Approaches to Adaptation—Emerging Opportunities

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Ecosystem-based adaptation (EBA), defined as the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (CBD, 2009), integrates the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe et al., 2011; see IPCC AR5 WGII Chapters 3, 4, 5, 8, 9, 13, 14, 15, 16, 19, 22, 25, and 27). EBA is implemented through the sustainable management of natural resources and conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls et al., 2009). It also sets out to take into account the multiple social, economic, and cultural co-benefits for local communities (CBD COP 10 Decision X/33).

EBA can be combined with, or even serve as a substitute for, the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls, and levees adversely affect biodiversity, potentially resulting in maladaptation due to damage to ecosystem regulating services (Campbell et al., 2009; Munroe et al., 2011). There is some evidence that the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). EBA offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes. Well-integrated EBA can be more cost effective and sustainable than non-integrated physical engineering approaches (Jones et al., 2012), and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches (CBD, 2009). In addition, EBA yields economic, social, and environmental co-benefits in the form of ecosystem goods and services (World Bank, 2009).

EBA is applicable in both developed and developing countries. In developing countries where economies depend more directly on the provision of ecosystem services (Vignola et al., 2009), EBA may be a highly useful approach to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang et al., 2013). EBA projects may be developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan et al., 2012, Midgley et al., 2012; Roberts et al., 2012).

Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and enhanced baseflows, flood regulation and protection services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Opperman et al., 2009; Midgley et al., 2012)

- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands, and deltas) to provide effective measure against storm-surges, saline intrusion, and coastal erosion (Jonkman et al., 2013)
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision. Traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques.
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes

Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach (CBD, 2009). The examples of EBA are too few and too recent to assess either the risks or the benefits comprehensively at this stage. EBA is still a developing concept but should be considered alongside adaptation options based more on engineering works or social change, and existing and new cases used to build understanding of when and where its use is appropriate.

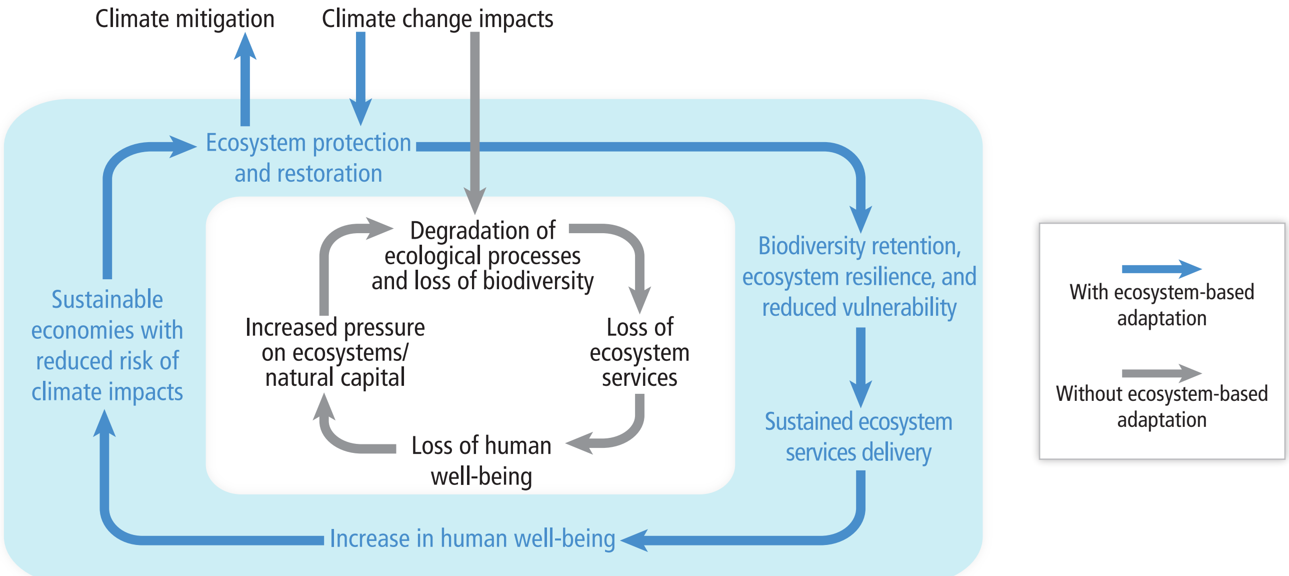

Figure EA-1 | Adapted from Munang et al. (2013). Ecosystem-based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.

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GC

Gender and Climate Change

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Gender, along with sociodemographic factors of age, wealth, and class, is critical to the ways in which climate change is experienced. There are significant gender dimensions to impacts, adaptation, and vulnerability. This issue was raised in WGII AR4 and SREX reports (Adger et al., 2007; IPCC, 2012), but for the AR5 there are significant new findings, based on multiple lines of evidence on how climate change is differentiated by gender, and how climate change contributes to perpetuating existing gender inequalities. This new research has been undertaken in every region of the world (e.g. Brouwer et al., 2007; Buechler, 2009; Nelson and Stathers, 2009; Nightingale, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Omolo, 2011; Resureccion, 2011).

Gender dimensions of vulnerability derive from differential access to the social and environmental resources required for adaptation. In many rural economies and resource-based livelihood systems, it is well established that women have poorer access than men to financial resources, land, education, health, and other basic rights. Further drivers of gender inequality stem from social exclusion from decision-making processes and labor markets, making women in particular less able to cope with and adapt to climate change impacts (Paavola, 2008; Djoudi and Brockhaus, 2011; Rijkers and Costa, 2012). These gender inequalities manifest themselves in gendered livelihood impacts and feminisation of responsibilities: whereas both men and women experience increases in productive roles, only women experience increased reproductive roles (Resureccion, 2011; Section 9.3.5.1.5, Box 13-1). A study in Australia, for example, showed how more regular occurrence of drought has put women under increasing pressure to earn off-farm income and contribute to more on-farm labor (Alston, 2011). Studies in Tanzania and Malawi demonstrate how women experience food and nutrition insecurity because food is preferentially distributed among other family members (Nelson and Stathers, 2009; Kakota et al., 2011).

AR4 assessed a body of literature that focused on women's relatively higher vulnerability to weather-related disasters in terms of number of deaths (Adger et al., 2007). Additional literature published since that time adds nuances by showing how socially constructed gender differences affect exposure to extreme events, leading to differential patterns of mortality for both men and women (*high confidence*; Section 11.3.3, Table 12-3). Statistical evidence of patterns of male and female mortality from recorded extreme events in 141 countries between 1981 and 2002 found that disasters kill women at an earlier age than men (Neumayer and Plümper, 2007; see also Box 13-1). Reasons for gendered differences in mortality include various socially and culturally determined gender roles. Studies in Bangladesh, for example, show that women do not learn to swim and so are vulnerable when exposed to flooding (Röhr, 2006) and that, in Nicaragua, the construction of gender roles means that middle-class women are expected to stay in the house, even during floods and in risk-prone areas (Bradshaw, 2010). Although the differential vulnerability of women to extreme events has long been understood, there is now increasing evidence to show how gender roles for men can affect their vulnerability. In particular, men are often expected to be brave and heroic, and engage in risky life-saving behaviors that increase their likelihood of mortality (Box 13-1). In Hai Lang district, Vietnam, for example, more men died than women as a result of their involvement in search and rescue and protection of fields during flooding (Campbell et al., 2009). Women and girls are more likely to become victims of domestic violence after a disaster, particularly when they are living in emergency accommodation, which has been documented in the USA and Australia (Jenkins and Phillips, 2008; Anastario et al., 2009; Alston, 2011; Whittenbury, 2013; see also Box 13-1).

Heat stress exhibits gendered differences, reflecting both physiological and social factors (Section 11.3.3). The majority of studies in European countries show women to be more at risk, but their usually higher physiological vulnerability can be offset in some circumstances by relatively lower social vulnerability (if they are well connected in supportive social networks, for example). During the Paris heat wave, unmarried men were at greater risk than unmarried women, and in Chicago elderly men were at greatest risk, thought to reflect their lack of connectedness in social support networks which led to higher social vulnerability (Kovats and Hajat, 2008). A multi-city study showed geographical variations in the relationship between sex and mortality due to heat stress: in Mexico City, women had a higher risk of mortality than men, although the reverse was true in Santiago and São Paulo (Bell et al., 2008).

Recognizing gender differences in vulnerability and adaptation can enable gender-sensitive responses that reduce the vulnerability of women and men (Alston, 2013). Evaluations of adaptation investments demonstrate that those approaches that are not sensitive to gender dimensions and other drivers of social inequalities risk reinforcing existing vulnerabilities (Vincent et al., 2010; Arora-Jonsson, 2011; Figueiredo and Perkins, 2012). Government-supported interventions to improve production through cash-cropping and non-farm enterprises in rural economies, for example, typically advantage men over women because cash generation is seen as a male activity in rural areas (Gladwin et al., 2001; see also Section 13.3.1). In contrast, rainwater and conservation-based adaptation initiatives may require additional labor, which women cannot necessarily afford to provide (Baiphethi et al., 2008). Encouraging gender-equitable access to education and strengthening of social capital are among the best means of improving adaptation of rural women farmers (Goulden et al., 2009; Vincent et al., 2010; Below et al., 2012) and could be used to complement existing initiatives mentioned above that benefit men. Rights-based approaches to development can inform adaptation efforts as they focus on addressing the ways in which institutional practices shape access to resources and control over decision-making processes, including through the social construction of gender and its intersection with other factors that shape inequalities and vulnerabilities (Tschakert and Machado, 2012; Bee et al., 2013; Tschakert, 2013; see also Section 22.4.3 and Table 22-5).

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HS

Heat Stress and Heat Waves

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According to WGI, it is *very likely* that the number and intensity of hot days have increased markedly in the last three decades and *virtually certain* that this increase will continue into the late 21st century. In addition, it is *likely* (*medium confidence*) that the occurrence of heat waves (multiple days of hot weather in a row) has more than doubled in some locations, but *very likely* that there will be more frequent heat waves over most land areas after mid-century. Under a medium warming scenario, Coumou et al. (2013) predicted that the number of monthly heat records will be more than 12 times more common by the 2040s compared to a non-warming world. In a longer time perspective, if the global mean temperature increases to +7°C or more, the habitability of parts of the tropics and mid-latitudes will be at risk (Sherwood and Huber, 2010). Heat waves affect natural and human systems directly, often with severe losses of lives and assets as a result, and may act as triggers of tipping points (Hughes et al., 2013). Consequently, heat stress plays an important role in several key risks noted in Chapter 19 and CC-KR.

Economy and Society (Chapters 10, 11, 12, 13)

Environmental heat stress has already reduced the global labor capacity to 90% in peak months with a further predicted reduction to 80% in peak months by 2050. Under a high warming scenario (RCP8.5), labor capacity is expected to be less than 40% of present-day conditions in peak months by 2200 (Dunne et al., 2013). Adaptation costs for securing cooling capacities and emergency shelters during heat waves will be substantial.

Heat waves are associated with social predicaments such as increasing violence (Anderson, 2012) as well as overall health and psychological distress and low life satisfaction (Tawatsupa et al., 2012). Impacts are highly differential with disproportional burdens on poor people, elderly people, and those who are marginalized (Wilhelmi et al., 2012). Urban areas are expected to suffer more due to the combined effect of climate and the urban heat island effect (Fischer et al., 2012; see also Section 8.2.3.1). In low- and medium-income countries, adaptation to heat stress is severely restricted for most people in poverty and particularly those who are dependent on working outdoors in agriculture, fisheries, and construction. In small-scale agriculture, women and children are particularly at risk due to the gendered division of labor (Croppenstedt et al., 2013). The expected increase in wildfires as a result of heat waves (Pechony and Shindell, 2010) is a concern for human security, health, and ecosystems. Air pollution from wildfires already causes an estimated 339,000 premature deaths per year worldwide (Johnston et al., 2012).

Human Health (Chapter 11)

Morbidity and mortality due to heat stress is now common all over the world (Barriopedro et al., 2011; Nitschke et al., 2011; Rahmstorf and Coumou, 2011; Diboulo et al., 2012; Hansen et al., 2012). Elderly people and people with circulatory and respiratory diseases are also vulnerable even in developed countries; they can become victims even inside their own houses (Honda et al., 2011). People in physical work are at particular risk as such work produces substantial heat within the body, which cannot be released if the outside temperature and humidity is above certain limits (Kjellstrom et al., 2009). The risk of non-melanoma skin cancer from exposure to UV radiation during summer months increases with temperature (van der Leun, et al., 2008). High temperatures are also associated with an increase in air-borne allergens acting as triggers for respiratory illnesses such as asthma, allergic rhinitis, conjunctivitis, and dermatitis (Beggs, 2010).

Ecosystems (Chapters 4, 5, 6, 30)

Tree mortality is increasing globally (Williams et al., 2013) and can be linked to climate impacts, especially heat and drought (Reichstein et al., 2013), even though attribution to climate change is difficult owing to lack of time series and confounding factors. In the Mediterranean region, higher fire risk, longer fire season, and more frequent large, severe fires are expected as a result of increasing heat waves in combination with drought (Duguy et al., 2013; see also Box 4.2).

Marine ecosystem shifts attributed to climate change are often caused by temperature extremes rather than changes in the average (Pörtner and Knust, 2007). During heat exposure near biogeographical limits, even small (<0.5°C) shifts in temperature extremes can have large effects, often exacerbated by concomitant exposures to hypoxia and/or elevated CO_2 levels and associated acidification (*medium confidence*; Hoegh-Guldberg et al., 2007; see also Figure 6-5; Sections 6.3.1, 6.3.5, 30.4, 30.5; CC-MB).

Most coral reefs have experienced heat stress sufficient to cause frequent mass coral bleaching events in the last 30 years, sometimes followed by mass mortality (Baker et al., 2008). The interaction of acidification and warming exacerbates coral bleaching and mortality (*very high confidence*).Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and through the impact of invasive subtropical species (*high confidence*; Sections 5, 6, 30.4, 30.5, CC-CR, CC-MB).

Agriculture (Chapter 7)

Excessive heat interacts with key physiological processes in crops. Negative yield impacts for all crops past +3°C of local warming without adaptation, even with benefits of higher CO_2 and rainfall, are expected even in cool environments (Teixeira et al., 2013). For tropical systems where moisture availability or extreme heat limits the length of the growing season, there is a high potential for a decline in the length of the growing season and suitability for crops (*medium evidence*, *medium agreement*; Jones and Thornton, 2009). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat-stressed by the 2050s.

There is *high confidence* that high temperatures reduce animal feeding and growth rates (Thornton et al., 2009). Heat stress reduces reproductive rates of livestock (Hansen, 2009), weakens their overall performance (Henry et al., 2012), and may cause mass mortality of animals in feedlots during heat waves (Polley et al., 2013). In the USA, current economic losses due to heat stress of livestock are estimated at several billion US$ annually (St-Pierre et al., 2003).

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KR

A Selection of the Hazards, Key Vulnerabilities, Key Risks, and Emergent Risks Identified in the WGII Contribution to the Fifth Assessment Report

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The accompanying table provides a selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapters 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30). Key risks are determined by hazards interacting with vulnerability and exposure of human systems, and ecosystems or species. The table underscores the complexity of risks determined by various climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, unsustainable and rapid urbanization, other demographic changes, failure in governance and inadequate governmental attention to risk reduction, and tolerance limits of species and ecosystems that often provide important services to vulnerable communities, generate the context in which climatic change related harm and loss can occur. The table illustrates that current global megatrends (e.g., urbanization and other demographic changes) in combination and in specific development context (e.g., in low-lying coastal zones), can generate new systemic risks in their interaction with climate hazards that exceed existing adaptation and risk management capacities, particularly in highly vulnerable regions, such as dense urban areas of low-lying deltas. A representative set of lines of sight is provided from across WGI and WGII. See Section 19.6.2.1 for a full description of the methods used to select these entries.

Table KR-1 | Examples of hazards/stressors, key vulnerabilities, key risks, and emergent risks.

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Terrestrial and Inland Water Systems (Chapter 4)	Rising air, soil, and water temperature (Sections 4.2.4, 4.3.2, 4.3.3)	Exceedance of eco-physiological climate tolerance limits of species (limited coping and adaptive capacities), increased viability of alien organisms	Risk of loss of native biodiversity, increase in non-native organism dominance	Cascades of native species loss due to interdependencies
		Health response to spread of temperature-sensitive vectors (insects)	Risk of novel and/or much more severe pest and pathogen outbreaks	Interactions among pests, drought, and fire can lead to new risks and large negative impacts on ecosystems.
	Change in seasonality of rain (Section 4.3.3)	Increasing susceptibility of plants and ecosystem services, due to mismatch between plant life strategy and growth opportunities	Changes in plant functional type mix leading to biome change with respective risks for ecosystems and ecosystem services	Fire-promoting grasses grow in winter-rainfall areas and provide fuel in dry summers.
Ocean Systems (Chapter 6)	Rising water temperature, increase of (thermal and haline) stratification, and marine acidification (Section 6.1.1)	Tolerance limits of endemic species surpassed (limited coping and adaptive capacities), increased abundance of invasive organisms, high susceptibility and sensitivity of warm water coral reefs and respective ecosystem services for coastal communities (Sections 6.3.1, 6.4.1)	Risk of loss of endemic species, mixing of ecosystem types, increased dominance of invasive organisms. Increasing risk of loss of coral cover and associated ecosystem with reduction of biodiversity and ecosystem services (Section 6.3.1)	Enhancement of risk as a result of interactions, e.g., acidification and warming on calcareous organisms (Section 6.3.5)
		New vulnerabilities can emerge as a result of shifted productivity zones and species distribution ranges, largely from low to high latitudes (Sections 6.3.4, 6.5.1), shifting fishery catch potential with species migration (Sections 6.3.1, 6.5.2, 6.5.3)	Risks due to unknown productivity and services of new ecosystem types (Sections 6.4.1, 6.5.3)	Enhancement of risk due to interactions of warming, hypoxia, acidification, new biotic interactions (Sections 6.3.5, 6.3.6)
	Expansion of oxygen minimum zones and coastal dead zones with stratification and eutrophication (Section 6.1.1)	Increasing susceptibility because hypoxia tolerance limits of larger animals surpassed, habitat contraction and loss for midwater fishes and benthic invertebrates (Section 6.3.3)	Risk of loss of larger animals and plants, shifts to hypoxia-adapted, largely microbial communities with reduced biodiversity (Section 6.3.3)	Enhancement of risk due to expanding hypoxia in warming and acidifying oceans (Section 6.3.5)
	Enhanced harmful algal blooms in coastal areas due to rising water temperature (Section 6.4.2.3)	Increasing susceptibility and limited adaptive capacities of important ecosystems and valuable services due to already existing multiple stresses (Sections 6.3.5, 6.4.1)	Increasing risk due to enhanced frequency of dinoflagellate blooms and respective potential losses and degradations of coastal ecosystems and ecosystem services (Section 6.4.2)	Disproportionate enhancement of risk due to interactions of various stresses (Section 6.3.5)
Food Security and Food Production Systems (Chapter 7)	Rising average temperatures and more frequent extreme temperatures (Sections 7.1, 7.2, 7.4, 7.5)	Susceptibility of all elements of the food system from production to consumption, particularly for key grain crops	Risk of crop failures, breakdown of food distribution and storage processes	Increase in the global population to about 9 billion combined with rising temperatures and other trace gases such as ozone affecting food production and quality. Upper temperature limit to the ability of some food systems to adapt
	Extreme precipitation and droughts (Section 7.4)	Crops, pasture, and husbandry are susceptible and sensitive to drought and extreme precipitation.	Risk of crop failure, risk of limited food access and quality	Flood and droughts affect crop yields and quality, and directly affect food access in most developing countries. (Section 7.4)
Urban Areas (Chapter 8)	Inland flooding (Sections 8.2.3, 8.2.4)	Large numbers of people exposed in urban areas to flood events. Particularly susceptible are people in low-income informal settlements with inadequate infrastructure (and often on flood plains or along river banks). These bring serious environmental health consequences from overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure and widespread impermeable surfaces. Local governments are often unable or unwilling to give attention to needed flood-related disaster risk reduction. Much of the urban population unable to get or afford housing that protects against flooding, or insurance. Certain groups are more sensitive to ill health from flood impacts, which may include increased mosquito- and water-borne diseases.	Risks of deaths and injuries and disruptions to livelihoods/incomes, food supplies, and drinking water	In many urban areas, larger and more frequent flooding impacting much larger population. No insurance available or impacts reaching the limits of insurance. Shift in the burden of risk management from the state to those at risk, leading to greater inequality and property blight, abandonment of urban districts, and the creation of high-risk/high-poverty spatial traps
	Coastal flooding (including sea level rise and storm surge) (Sections 8.1.4, 8.2.3, 8.2.4)	High concentrations of people, businesses, and physical assets including critical infrastructure exposed in low-lying and unprotected coastal zones. Particularly susceptible is the urban population that is unable to get or afford housing that protects against flooding or insurance. The local government is unable or unwilling to give needed attention to disaster risk reduction.	Risks from deaths and injuries and disruptions to livelihoods/incomes, food supplies, and drinking water	Additional 2 billion or so urban dwellers expected over the next three decades Sea level rise means increasing risks over time, yet with high and often increasing concentrations of population and economic activities on the coasts. No insurance available or reaching the limits of insurance; shift in the burden of risk management from the state to those at risk leading to greater inequality and property blight, abandonment of urban districts, and the creation of high-risk/high-poverty spatial traps

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Urban Areas (continued) (Chapter 8)	Heat and cold (including urban heat island effect) (Section 8.2.3)	Particularly susceptible is a large and often increasing urban population of infants, young children, older age groups, expectant mothers, people with chronic diseases or compromised immune system in settlements exposed to higher temperatures (especially in heat islands) and unexpected cold spells. Inability of local organizations for health, emergency, and social services to adapt to new risk levels and set up needed initiatives for vulnerable groups	Risk of mortality and morbidity increasing, including shifts in seasonal patterns and concentrations due to hot days with higher or more prolonged high temperatures or unexpected cold spells. Avoiding risks often most difficult for low-income groups	Duration and variability of heat waves increasing risks over time for most locations owing to interactions with multiple stressors such as air pollution
	Water shortages and drought in urban regions (Sections 8.2.3, 8.2.4)	Lack of piped water to homes of hundreds of millions of urban dwellers. Many urban areas subject to water shortages and irregular supplies, with constraints on increasing supplies. Lack of capacity and resilience in water management regimes including rural–urban linkages. Dependence on water resources in energy production systems	Risks from constraints on urban water provision services to people and industry with human and economic impacts. Risk of damage and loss to urban ecology and its services including urban and peri-urban agriculture.	Cities' viability may be threatened by loss or depletion of freshwater sources—including for cities dependent on distant glacier melt water or on depleting groundwater resources.
	Changes in urban meteorological regimes lead to enhanced air pollution. (Section 8.2.3)	Increases in exposure and in pollution levels with impacts most serious among physiologically susceptible populations. Limited coping and adaptive capacities, due to lacking implementation of pollution control legislation of urban governments	Increasing risk of mortality and morbidity, lowered quality of life. These risks can also undermine the competitiveness of global cities to attract key workers and investment.	Complex and compounding health crises
	Geo-hydrological hazards (salt water intrusion, mud/land slides, subsidence) (Sections 8.2.3, 8.2.4)	Local structures and networked infrastructure (piped water, sanitation, drainage, communications, transport, electricity, gas) particularly susceptible. Inability of many low-income households to move to housing on safer sites.	Risk of damage to networked infrastructure. Risk of loss of human life and property	Potential for large local and aggregate impacts Knock-on effects for urban activities and well-being
	Wind storms with higher intensity (Sections 8.1.4, 8.2.4)	Substandard buildings and physical infrastructure and the services and functions they support particularly susceptible. Old and difficult to retrofit buildings and infrastructure in cities Local government unable or unwilling to give attention to disaster risk reduction (limited coping and adaptive capacities)	Risk of damage to dwellings, businesses, and public infrastructure. Risk of loss of function and services. Challenges to recovery, especially where insurance is absent	Challenges to individuals, businesses, and public agencies where the costs of retrofitting are high and other sectors or interests capture investment budgets; potential for tensions between development and risk reduction investments
	Changing hazard profile including novel hazards and new multi-hazard complexes (Sections 8.1.4, 8.2.4)	Newly exposed populations and infrastructure, especially those with limited capacity for multi-hazard risk forecasting and where risk reduction capacity is limited, e.g., where risk management planning is overly hazard specific including where physical infrastructure is predesigned in anticipation of other risks (e.g., geophysical rather than hydrometeorological)	Risks from failures within coupled systems, e.g., reliance of drainage systems on electric pumps, reliance of emergency services on roads and telecommunications. Potential of psychological shock from unanticipated risks	Loss of faith in risk management institutions. Potential for extreme impacts that are magnified by a lack of preparation and capacity in response
	Compound slow-onset hazards including rising temperatures and variability in temperature and water (Sections 8.2.2, 8.2.4)	Large sections of the urban population in low- and middle-income nations with livelihoods or food supplies dependent on urban and peri-urban agriculture are especially susceptible.	Risk of damage to or degradation of soils, water catchment capacity, fuel wood production, urban and peri-urban agriculture, and other productive or protective ecosystem services. Risk of knock-on impacts for urban and peri-urban livelihoods and urban health	Collapsing of peri-urban economies and ecosystem services with wider implications for urban food security, service provision, and disaster risk reduction
	Climate change–induced or intensified hazard of more diseases and exposure to disease vectors (Sections 8.2.3, 8.2.4)	Large urban population that is exposed to food-borne and water-borne diseases and to malaria, dengue, and other vector-borne diseases that are influenced by climate change	Risk due to increases in exposure to these diseases	Lack of capacity of public health system to simultaneously address these health risks with other climate-related risks such as flooding
Rural Areas (Chapter 9)	Drought in pastoral areas (Sections 9.3.3.1, 9.3.5.2)	Increasing vulnerability due to encroachment on pastoral rangelands, inappropriate land policy, misperception and undermining of pastoral livelihoods, conflict over natural resources, all driven by remoteness and lack of voice	Risk of famine Risk of loss of revenues from livestock trade	Increasing risks for rural livelihoods through animal disease in pastoral areas combined with direct impacts of drought
	Effects of climate change on artisanal fisheries (Sections 9.3.3.1, 9.3.5.2)	Artisanal fisheries affected by pollution and mangrove loss, competition from aquaculture, and the neglect of the sector by governments and researchers as well as complex property rights	Risk of economic losses for artisanal fisherfolk, due to declining catches and incomes and damage to fishing gear and infrastructure	Reduced dietary protein for those consuming artisanally caught fish, combined with other climate-related risks

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Rural Areas (continued) (Chapter 9)	Water shortages and drought in rural areas (Section 9.3.5.1.1)	Rural people lacking access to drinking and irrigation water. High dependence of rural people on natural resource-related activities. Lack of capacity and resilience in water management regimes (institutionally driven). Increased water demand from population pressure	Risk of reduced agricultural productivity of rural people, including those dependent on rainfed or irrigated agriculture, or high-yield varieties, forestry, and inland fisheries. Risk of food insecurity and decrease in incomes. Decreases in household nutritional status (Section 9.3.5.1)	Impacts on livelihoods driven by interaction with other factors (water management institutions, water demand, water used by non-food crops), including potential conflicts for access to water. Water-related diseases
Human Health (Chapter 11)	Increasing frequency and intensity of extreme heat	Older people living in cities are most susceptible to hot days and heat waves, as well as people with preexisting health conditions. (Section 11.3)	Risk of increased mortality and morbidity during hot days and heat waves. (Section 11.4.1) Risk of mortality, morbidity, and productivity loss, particularly among manual workers in hot climates	The number of elderly people is projected to triple from 2010 to 2050. This can result in overloading of health and emergency services.
	Increasing temperatures, increased variability in precipitation	Poorer populations are particularly susceptible to climate-induced reductions in local crop yields. Food insecurity may lead to undernutrition. Children are particularly vulnerable. (Section 11.3)	Risk of a larger burden of disease and increased food insecurity for particular population groups. Increasing risk that progress in reducing mortality and morbidity from undernutrition may slow or reverse. (Section 11.6.1)	Combined effects of climate impacts, population growth, plateauing productivity gains, land demand for livestock, biofuels, persistent inequality, and ongoing food insecurity for the poor
	Increasing temperatures, changing patterns of precipitation	Non-immune populations who are exposed to water- and vector-borne diseases that are sensitive to meteorological conditions (Section 11.3)	Increasing health risks due to changing spatial and temporal distribution of diseases strains public health systems, especially if this occurs in combination with economic downturn. (Section 11.5.1)	Rapid climate and other environmental change may promote emergence of new pathogens.
	Increased variability in precipitation	People exposed to diarrhea aggravated by higher temperatures, and unusually high or low precipitation (Section 11.3)	Risk that the progress to date in reducing childhood deaths from diarrheal disease is compromised (Section 11.5.2)	Increased rate of failure of water and sanitation infrastructure due to climate change leading to higher diarrhea risk
Livelihoods and Poverty (Chapter 13)	Increasing frequency and severity of droughts, coupled with decreasing rainfall and/or increased unpredictability of rainfall (Sections 13.2.1.2, 13.2.1.4, 13.2.2.2)	Poorly endowed farmers (high and persistent poverty), particularly in drylands, are susceptible to these hazards, since they have a very limited ability to compensate for losses in water-dependent farming systems and/or livestock.	Risk of irreversible harm due to short time for recovery between droughts, approaching tipping point in rainfed farming system and/or pastoralism	Deteriorating livelihoods stuck in poverty traps, heightened food insecurity, decreased land productivity, outmigration, and new urban poor in LICs and MICs
	Floods and flash floods in informal urban settlements and mountain environments, destroying physical assets (e.g., homes, roads, terraces, irrigation canals) (Sections 13.2.1.1, 13.2.1.3, 13.2.1.4)	High exposure and susceptibility of people, particularly children and elderly, as well as disabled in flood-prone areas. Inadequate infrastructure, culturally imposed gender roles, and limited ability to cope and adapt due to political and institutional marginalization and high poverty adds to the susceptibility of these people in informal urban settlements; limited political interest in development and building adaptive capacity	Risk of high morbidity and mortality due to floods and flash floods. Factors that further increase risk may include a shift from transient to chronic poverty due to eroded human and economic assets (e.g., labor market) and economic losses due to infrastructure damage.	Exacerbated inequality between better-endowed households able to invest in flood-control measures and/or insurance and increasingly vulnerable populations prone to eviction, erosion of livelihoods, and outmigration
	Increased variability of precipitation; shifts in mean climate and extreme events (Sections 13.2.1.1, 13.2.1.4)	Limited ability to cope owing to exhaustion of social networks, especially among the elderly and female-headed households; mobilization of labor and food no longer possible	Hazard combines with vulnerability to shift populations from transient to chronic poverty due to persistent and irreversible socioeconomic and political marginalization. In addition, the lack of governmental support, as well as limited effectiveness of response options, increase the risk.	Increasing yet invisible multidimensional vulnerability and deprivation at the convergence of climatic hazards and socioeconomic stressors
	Successive and extreme events (floods, droughts) coupled with increasing temperatures and rising water demand (Sections 13.2.1.1, 13.2.1.5)	Rural communities are particularly susceptible, due to the marginalization of rural water users to the benefit of urban users, given political and economic priorities (e.g., Australia, Andes, Himalayas, Caribbean).	Risk of loss of rural livelihoods, severe economic losses in agriculture, and damage to cultural values and identity; mental health impacts (including increased rates of suicide)	Loss of rural livelihoods that have existed for generations, heightened outmigration to urban areas; emergence of new poverty in MICs and HICs
	Sea level rise (Sections 13.1.4, 13.2.1.1, 13.2.2.1, 13.2.2.3)	High number of people exposed in low-lying areas coupled with high susceptibility due to multidimensional poverty, limited alternative livelihood options among poor households, and exclusion from institutional decision-making structures	Risk of severe harm and loss of livelihoods. Potential loss of common-pool resources; of sense of place, belonging, and identity, especially among indigenous populations	Loss of livelihoods and mental health risks due to radical change in landscape, disappearance of natural resources, and potential relocation; increased migration
	Increasing temperatures and heat waves (Sections 13.2.1.5, 13.2.2.3, 13.2.2.4)	Agricultural wage laborers, small-scale farmers in areas with multidimensional poverty and economic marginalization, children in urban slums, and the elderly are particularly susceptible.	Risk of increased morbidity and mortality due to heat stress, among male and female workers, children, and the elderly, limited protection due to socioeconomic discrimination and inadequate governmental responses	Declining labor pool for agriculture coupled with new challenges for rural health care systems in LICs and MICs; aging and low-income populations without safety nets in HICs at risk

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Livelihoods and Poverty (continued) (Chapter 13)	Increased variability of rainfall and/or extreme events (floods, droughts, heat waves) (Sections 13.2.1.1, 13.2.1.3, 13.2.1.4, 13.2.1.5)	People highly dependent on rainfed agriculture are particularly at risk. Persistent poverty among subsistence farmers and urban wage laborers who are net buyers of food with limited coping mechanisms	Risk of crop failure, spikes in food prices, reduction in consumption to protect household assets, risk of food insecurity, shifts from transient to chronic poverty due to limited ability to reduce risks	Food riots, child food poverty, global food crises, limits of insurance and other risk-spreading strategies
	Changing rainfall patterns (temporally and spatially)	Households or people with a high dependence on rainfed agriculture and little access to alternative modes of income	Risks of crop failure, food shortage, severe famine	Coincidence of hazard with periods of high global food prices leads to risk of failure of coping strategies and adaptation mechanisms such as crop insurance (risk spreading).
	Stressor from soaring demand (and prices) for biofuel feedstocks due to climate policies	Farmers and groups that have unclear and/or insecure land tenure arrangements are exposed to the dispossession of land due to land grabbing in developing countries.	Risk of harm and loss of livelihoods for some rural residents due to soaring demand for biofuel feedstocks and insecure land tenure and land grabbing	Creation of large groups of landless farmers unable to support themselves. Social unrest due to disparities between intensive energy production and neglected food production
	Increasing frequency of extreme events (droughts, floods), e.g., if 1:20 year drought/flood becomes 1:5 year drought/flood	Pastoralists and small farmers subject to damage to their productive assets (e.g., herds of livestock; dykes, fences, terraces)	Risk of the loss of livelihoods and harm due to shorter time for recovery between extremes. Pastoralists restocking after a drought may take several years; in terraced agriculture, need to rebuild terraces after flood, which may take several years	Collapse of coping strategies with risk of collapsing livelihoods. Adaptation mechanisms such as insurance fail due to increasing frequency of claims.
Emergent Risks and Key Vulnerabilities (Chapter 19)	Warming and drying (precipitation changes of uncertain magnitude) (WGI AR5 TS 5.3; SPM; Sections 11.3, 12.4)	Limits to coping capacity to deal with reduced water availability; increasing exposure and demand due to population increase; conflicting demands for alternative water uses; sociocultural constraints on some adaptation options (Sections 19.2.2, 19.3.2.2, 19.6.1.1, 19.6.3.4)	Risk of harm and loss due to livelihood degradation from systematic constraints on water resource use that lead to supply falling far below demand. In addition, limited coping and adaptation options increase the risk of harm and loss. (Sections 19.3.2.2, 19.6.3.4)	Competition for water from diverse sectors (e.g., energy, agriculture, industry) interacts with climate changes to produce locally severe shortages. (Sections 19.3.2.2, 19.6.3.4)
	Changes in regional and seasonal temperature and precipitation over land (WGI AR5 TS 5.3; SPM; Sections 11.3, 12.4)	Communities highly dependent on ecosystem services (Sections 19.2.2.1, 19.3.2.1) which are negatively affected by changes in regional and seasonal temperature	Risk of large-scale species richness loss over most of the global land surface. 57 ± 6% of widespread and common plants and 34 ± 7% of widespread and common animals are expected to lose ≥50% of their current climatic range by the 2080s leading to loss of services. (Section 19.3.2.1)	Widespread loss of ecosystem services, including: provisioning, such as food and water; regulating, such as the control of climate and disease; supporting, such as nutrient cycles and crop pollination; and cultural, such as spiritual and recreational benefit (Sections 19.3.2.1, 19.6.3.4)
Africa (Chapter 22)	Increasing temperature	Children, pregnant women, and those with compromised health status are particularly at risk for temperature-related changes in diarrheal and vector-borne diseases, and for temperature-related reductions in crop yields. Outdoor workers, older adults, and young children are most susceptible to hot weather and heat waves. (Sections 22.3.5.2, 22.3.5.4)	Risk of changes in the geographic distribution, seasonality, and incidence of infectious diseases, leading to increases in the health burden. Risk of increased burdens of stunting in children. Risk of increase in morbidity and mortality during hot days and heat waves	Interactions among factors lead to emerging and re-emerging epidemics.
		Populations dependent on aquatic systems and aquatic ecosystem services that are sensitive to increased water temperatures	Loss of aquatic ecosystems and risks for people who might depend on these resources; reduction in freshwater fisheries production (Sections 22.3.2.2, 22.3.4.4)	Risk of loss of livelihoods due to interactions of loss of ecosystem services and other climate-related stressors on poor communities
		Rural and urban populations whose food and livelihood security is diminished	Risk of harm and loss due to increased heat stress on crops and livestock resulting in reduced productivity; increased food storage losses due to spoilage (Sections 22.3.4.1, 22.3.4.2)	Range expansion of crop pests and diseases to high-elevation agroecosystems (Section 22.3.4.3)
	Extreme events, e.g., floods and flash floods (and drought)	Population groups living in informal settlements in highly exposed urban areas; women and children often the most vulnerable to disaster risk (Sections 22.3.6, 22.4.3)	Increasing risk of mortality, harm and losses due to water logging triggered by heavy rainfall events	Compounded risk of epidemics including diarrheal diseases (e.g., cholera)
		Susceptible groups include those who experience diminished access to food resulting from reduced capacity to transport, store, and market food, such as the urban poor.	Risk of food shortages and of damages to the food system due to storms and flooding	Food price spikes due to convergence of climatic and non-climatic forces that reduce food access for the poor whose income is disproportionately spent on food (Section 22.3.4.5)
		Children, pregnant women, and those with compromised health status are particularly vulnerable to reduced access to safe water and improved sanitation and increasing food insecurity. (Sections 22.3.5.2, 22.3.5.3)	Risk of crop and livestock losses from drought Risk of reduced water supply and quality for household use. (Sections 22.3.4.1, 22.3.4.2) Risk of increased incidence of food- and water-borne diseases (e.g., cholera) and undernutrition. Risk of drinking water contamination due to heavy precipitation events and flooding (Section 22.3.5.2)	Compound effects of high temperature and changes in rainfall on human and natural systems. Increased incidence of stunting in children (Section 22.3.5.3)

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Europe (Chapter 23)	Extreme weather events (Section 23.9)	Sectors with limited coping and adaptive capacity as well as high sensitivity to these extreme events, such as transport, energy, and health, are particularly susceptible.	Risk of new systemic threats due to stress on multiple and interconnected sectors. Risk of failure of service provision of one or more sectors	Disproportionate intensification of risk due to increasing interdependencies
	Climate change increases the spatial distribution and seasonality of pests and diseases. (Section 23.4.1, 23.4.3, 23.4.4)	High susceptibility of plants and animals that are exposed to pests and diseases	Risk of increases in crop losses and animal diseases or even fatalities of livestock	Increasing risks due to limited response options and various feedback processes in agriculture, e.g., use of pesticides or antibiotics to protect plants and livestock increases resistance of disease vectors
	Extreme weather events and reduced water availability due to climate change (Section 23.3.4)	Low adaptive capacity of power systems might lead to limited energy supply as well as higher supply costs during such extreme events and conditions.	Increasing risk of power shortages due to limited energy supply, e.g., of nuclear power plants due to limited cooling water during heat stress	Continued underinvestment in adaptive energy systems might increase the risk of mismatches between limited energy supply during these events and increased demands, e.g., during a heat wave.
Asia (Chapter 24)	Rising average temperatures and more frequent extreme temperatures, as well as changing rainfall patterns (temporally and spatially)	Food systems and food production systems for key grain crops, particularly rice and other cereal crop farming systems, are highly susceptible. (Section 24.4.4.3)	Risk of crop failures and lower crop yield also can increase the risk of major losses for farmers and rural livelihoods. (Section 24.4.4.3)	Increase in Asian population combined with rising temperatures affecting food production. Upper temperature limit to the ability of some food systems to adapt could be reached.
	Rising sea level	Paddy fields and farmers near the coasts are particularly susceptible. (Section 24.4.4.3)	Risk of loss of arable areas due to submergence (Section 24.4.4.3)	Migration of farming communities to higher elevation areas entails risks for migrants and receiving regions.
	Projected increase in frequency of various extreme events (heat wave, floods, and droughts) and sea level rise	Increasing exposure due to convergence of livelihood and properties into coastal megacities. People in areas that are not sufficiently protected against natural hazards are particularly susceptible.	Risk of loss of life and assets due to coastal floods accompanied by increasing vulnerabilities.	Projected increase in disruptions of basic services such as water supply, sanitation, energy provision, and transportation systems, which themselves could increase vulnerabilities
Australasia (Chapter 25)	Rising air and sea surface temperatures, drying trends, reduced snow cover, increased intensity of severe cyclones, ocean acidification (Section 25.2; Table 25-1; Figure 25-4; WGI AR5 Chapter 14 and Atlas)	Species that live in a limited climatic range and that suffer from habitat fragmentation as well as from external stressors (pollution, runoff, fishing, tourism, introduced predators, and pests) are especially susceptible. (Sections 25.6.1, 25.6.2)	Risk of significant change in community composition and structure of coral reefs and montane ecosystems and risk of loss of some native species in Australia (Sections 25.6.1, 25.6.2, 25.10.2)	Increasing risk from compound extreme events across time and space, and cumulative adaptation needs, with recovery and risk reduction measures hampered further by impacts and responses reaching across different levels of government (Sections 25.10.2, 25.10.3; Box 25-9)
	Increased extreme rainfall related to flood risk in many locations (Section 25.2; Table 25-1)	Adaptation deficit of existing infrastructure and settlements to current flood risk; expansion and densification of urban areas; effective adaptation includes transformative changes such as land-use controls and retreat. (Sections 25.3, 25.10.2; Box 25-8)	Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (Box 25-8; Section 25.10.2)	
	Continuing sea level rise, with projections spanning a particularly large range and continuing beyond 2100, even under mitigation scenarios (Section 25.2; Box 25-1; WGI AR5 Chapter 13)	Long-lived and high asset value coastal infrastructure and low-lying ecosystems are highly susceptible. Expansion of coastal populations and assets into coastal zones increases the exposure. Conflicting priorities constrain adaptation options and limit effective response strategies. (25.3, Box 25-1)	Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damages toward the upper end of projected ranges (Box 25-1; Sections 25.6.1, 25.6.2, 25.10.2)	
North America (Chapter 26)	Increases in frequency and/or intensity of extreme events, such as heavy precipitation, river and coastal floods, heat waves, and droughts (Sections 26.2.2, 26.3.1, 26.8.1)	Physical infrastructure in a declining state in urban areas particularly susceptible. Also increases in income disparities and limited institutional capacities might result in larger proportions of people susceptible to these stressors due to limited economic resources. (Sections 26.7, 26.8.2)	Risk of harm and loss in urban areas, particularly in coastal and dry environments due to enhanced vulnerabilities of social groups, physical systems, and institutional settings combined with the increases of extreme weather events (Section 26.8.1)	Inability to reduce vulnerability in many areas results in an increase in risk more so than change in physical hazard. (Section 26.8.3)
	Higher temperatures, decreases in runoff, and lower soil moisture due to climate change (Sections 26.2, 26.3)	Vulnerability of small rural landholders, particularly in Mexican agriculture, and of the poor in rural settlements (Sections 26.5, 26.8.2.2)	Risk of increased losses and decreases in agricultural production. Risk of food and job insecurity for small landholders and social groups in regions exposed to these phenomena (Sections 26.5, 26.8.2.2)	Increasing risks of social instability and local economic disruption due to internal migration (Sections 26.2.1, 26.8.3)

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
North America (continued) (Chapter 26)	Wildfires and drought conditions (Box 26-2)	Indigenous groups, low-income residents in peri-urban areas, and forest systems (Box 26-2; Section 26.8.2)	Risk of loss of ecosystem integrity, property loss, human morbidity, and mortality due to wildfires (Box 26-2; Section 26.8.3)	
	Extreme storm and heat events, air pollution, pollen, and infectious diseases (Section 26.6.1)	Susceptibility of individuals is determined by factors such as economic status, preexisting illness, age, and access to assets. (Section 26.6.1)	Increasing risk of extreme temperature-, storm-, pollen-, and infectious diseases–related human morbidity or mortality (Section 26.6.2)	
	River and coastal floods, and sea level rise (Sections 26.2.2, 26.4.2, 26.8.1)	Increasing exposure of populations, property, as well as ecosystems, partly resulting from overwhelmed drainage networks. Groups and economic sectors that highly depend on the functioning of different supply chains, public health institutions that can be disrupted, and groups that have limited coping capacities to deal with supply chain interruptions and disruptions to their livelihoods are particularly susceptible. (Sections 26.7, 26.8.1)	Risk of property damage, supply chain disruption, public health, water quality impairment, ecosystem disruption, infrastructure damage, and social system disruption from urban flooding due to river and coastal floods and floods of drainage networks (Sections 26.4.2, 26.8.1)	Multiple risks from interacting hazards on populations' livelihoods, infrastructure, and services (Sections 26.7, 26.8.3)
Central and South America (Chapter 27)	Reduced water availability in semi-arid regions and regions dependent on glacier meltwater; flooding in urban areas due to extreme precipitation (Sections 27.2.1, 27.3.3)	Groups that cannot keep agricultural livelihoods and are forced to migrate are especially vulnerable. Limited infrastructure and planning capacity can further increase the lack of coping and adaptive capacities to rapid changes expected (precipitation), especially in large cities.	Risk of loss of human lives, livelihood, and property	Increase in infectious diseases. Economic impacts due to reallocation of populations
	Ocean acidification and warming (Section 27.3.3; Box CC-OA)	Sensitivity of coral reef systems to ocean acidification and warming	Risk of loss of biodiversity (species) and risk of a reduced fishing capacity with respective impacts for coastal livelihoods	Economic losses and impact on food (fishery) production in certain regions
	Extremes of drought/ precipitation (Sections 27.2.1, 27.3.4)	Elevated CO_2 decreases nutrient contents in plants, especially nitrogen in relation to carbon in food products.	Risk of loss of (food) production and productivity in some regions where extreme events may occur. Need to adjust diet due to decrease in food quality (e.g., less protein due to lower nitrogen assimilation). Decrease in bioenergy production	Strong economic impacts related to the need to move crops to more suitable regions. Teleconnections (related to food quality) related to the intense exportation of food by the region. Impacts on energy system and carbon emissions with consequent increase in fossil fuel demand.
	Higher temperatures and humidity lead to a spread of vector-borne diseases in altitude and latitude. (Section 27.3.7)	People exposed and vulnerable to vector-borne diseases and an increase in mosquito biting rates that increase the probability of human infections	Risk of increase in morbidity and in disability-adjusted life years (DALYs); risk of loss of human lives; risk of decrease in school and labor productivity	High economic impacts owing to the necessity to increase the financing of health programs, as well as the costs of DALYs, increase in hospitals and medical infrastructure adequate to cope with increasing disease incidence rates, and the spread of diseases to newer regions
Polar Regions (Chapter 28)	Loss of multi-year ice and reductions in the spatial extent of summer sea ice (Sections 28.2.5, 28.3.2, 28.4.1)	Indigenous communities that depend on sea ice for traditional livelihoods are vulnerable to this hazard, particularly due to loss of breeding and foraging platforms for marine mammals.	Risk of loss of traditional livelihoods and food sources.	Top-down shifts in food webs
		Ecosystems are vulnerable owing to the shifts in the distribution and timing of ice algal and ocean phytoplankton blooms.	Risk of disruption of synchronized timing of zooplankton ontogeny and availability of prey. Increased variability in secondary production while zooplankton adapt to shifts in timing. Risks also to local marine food webs.	Bottom up shifts in food webs. Potential changes in pelagic and benthic coupling
	Ocean acidification (Sections 28.2.2, 28.3.2)	Tolerance limits of endemic species surpassed. Impacts on exoskeleton formation for some species and alteration of physiological and behavioral properties during larval development	Localized loss of endemic species, local impacts on marine food webs	Localized declines in commercial fisheries. Local declines in fish, shellfish, seabirds, and marine mammals
	Shifts in boundaries of marine eco-regions due to rising water temperature, shifts in mixed layer depth, changes in the distribution and intensity of ocean currents (Sections 28.2.2, 28.3.2)	Marine organisms that are susceptible to spatial shifts are particularly vulnerable.	Risk of changes in the structure and function of marine systems and potentially species invasions	Disputes over international fisheries and shared stocks

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Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
Polar Regions (continued) (Chapter 28)	Declining sea ice, changes in snow and ice timing and state, decreasing predictability of weather (Sections 28.1, 28.4.1)	Many traditional subsistence food sources—especially for indigenous peoples—such as Arctic marine and land mammals, fish, and waterfowl. Various traditional livelihoods are susceptible to these hazards.	Risk of loss of habitats and changes in migration patterns of marine species	Enhancement of risk to food security and basic nutrition—especially for indigenous peoples—from loss of subsistence foods and increased risk to subsistence hunters', herders', and fishers' health and safety in changing ice conditions
	Increased river and coastal flooding and erosion and thawing of permafrost (Sections 28.2.4, 28.3.1, 28.3.4)	Rural and remote communities as well as urban communities in low-lying Arctic areas are exposed. Susceptibility and limited coping capacity of community water supplies due to potential damages to infrastructure.	Community and public health infrastructure damaged resulting in disease from contamination and sea water intrusion	Reduced water quality and quantity may result in increased rates of infection, other medical problems, and hospitalizations.
	Extreme and rapidly changing weather, intense weather and precipitation events, rapid snow and ice melt, changing river and sea ice conditions, permafrost thaw (Section 28.2.4)	People living from subsistence travel and hunting, herding, and fishing, for example indigenous peoples in remote and isolated communities, are particularly susceptible.	Accidents, physical/mental injuries, death, and cold-related exposure, injuries, and diseases	Enhanced risks to safe travel or subsistence hunting, herding, fishing activities affect livelihoods and well-being.
	Diminished sea ice; earlier sea ice melt-out; faster sea ice retreat; thinner, less predictable ice in general; greater variability in snow melt/freeze; ice, weather, winds, temperatures, precipitation (Sections 28.2.5, 28.2.6, 28.4.1)	Livelihoods of many indigenous peoples (e.g., Inuit and Saami) depend upon subsistence hunting and access to and favorable conditions for animals. These livelihoods are susceptible. Also marine ecosystems are susceptible (e.g., marine mammals).	Risk of loss of livelihoods and damage due to, e.g., more difficult access to marine mammals associated with diminishing sea ice (a risk to the Inuit), and loss of access by reindeer to their forage under snow due to ice layers formed by warming winter temperatures and "rain on snow" (a risk to the Saami).	Enhanced risk of loss of livelihoods and culture of increasing numbers of indigenous peoples, exacerbated by increasing loss of lands and sea ice for hunting, herding, fishing due to enhanced petroleum and mineral exploration, and increased maritime traffic
Small Islands (Chapter 29)	Increases in intensity of tropical cyclones (WGI AR5 Sections 14.6, 14.8.4)	Various countries and communities are vulnerable to these hazards because of their high dependence on natural and ecological systems for security of settlements and tourism (Section 29.3.3.1), human health (Section 29.3.3.2), and water resources (Section 29.3.2).	Risk of loss of ecosystems, settlements, and infrastructure, as well as negative impacts on human health and island economies (Figure 29-4)	Increased risk of interactions of damages to ecosystems, settlements, island economies, and risks to human life (Section 29.6; Figure 29-4)
	Ocean warming and acidification leading to coral bleaching (Sections 29.3.1.2, 30.5.4.2, 30.5.6.1.1, 30.5.6.2)	Tropical island communities are highly dependent on coral reef ecosystems for subsistence life styles, food security, coastal protection and beach, and reef-based tourist economic activity, and hence are highly susceptible to the hazard of coral bleaching. (Sections 29.3.1.2, 30.6.2.1.2)	Risk of decline and possible loss of coral reef ecosystems through thermal stress. Risk of serious harm and loss of subsistence lifestyles. Risk of loss of coastal protection and beaches, risk of loss of tourist revenue (Sections 29.3.1.1, 29.3.1.2)	Impacts on human health and loss of subsistence lifestyles. Potential increase in internal migration/urbanization (Section 29.3.3.3; Chapter 9)
	Sea level rise (Sections 29.3.1.1, 30.3.1.2; WGI AR5 Section 3.7.1)	Many small island communities and associated settlements and infrastructure are in low-lying coastal zones (high exposure) and are also vulnerable to increasing inundation, erosion and wave incursion. (Sections 5.3.2, 29.3.1.1; Figure 29-2)	Risk of loss and harm due to sea level rise in small island communities. Global mean sea level is likely to increase by 0.35 to 0.70 m for Representative Concentration Pathway (RCP) 4.5 during the 21st century, threatening low-lying coastal areas and atoll islands. (Section 29.4.3, Table 29-1; WGI AR5 Section 13.5.1, Table 13.5)	Incremental upwards shift in sea-level baselines results in increased frequency and extent of marine flooding during high tides and episodic storm surges. These events could render soils and fresh groundwater resources unfit for human use before permanent inundation of low-lying areas. (Sections 29.3.1.1, 29.3.2, 29.3.3.1, 29.5.1)

Continued next page →

Table KR-1 (continued)

	Hazard	Key vulnerabilities	Key risks	Emergent risks
The Ocean (Chapter 30)	Increasing ocean temperatures. Increased frequency of thermal extremes	Corals and other organisms whose tolerance limits are exceeded are particularly susceptible (especially CBS, STG, SES, and EUS ocean regions). (Sections 6.2.2.1, 6.2.2.2, 30.5.2, 30.5.4, 30.5.5; Boxes CC-CR, 30.5.6, CC-OA)	Risk of increased mass coral bleaching and mortality (loss of coral cover) with severe risks for coastal fisheries, tourism, and coastal protection (Sections 6.3.2. 6.3.5, 5.4.2.4, 7.2.1.2, 6.4.1.4, 29.3.1.2, 30.5.2, 30.5.3, 30.5.4, 30.5.5; Box CC-CR)	Loss of coastal reef systems, risk of decreased food security and reduced livelihoods, and reduced coastal protection (Sections 7.2.1.2, 30.6.2.1, 30.6.5)
		Marine species and ecosystems as well as fisheries and coastal livelihoods and tourism that cannot cope or adapt to changing temperatures and changes in the distribution are particularly vulnerable, especially for HLSBS, CBS, STG, and EBUE. (Sections 6.3.2, 6.3.4, 7.3.2.6, 30.5; Box CC-BIO)	Risk for fishery and coastal livelihoods. Fishery opportunity changes as stock abundance may rise or fall; increased risk of disease and invading species impacting ecosystems and fisheries (Sections 6.3.5, 6.4.1.1, 6.5.3, 7.3.2.6, 7.4.2, 29.5.3, 29.5.4)	Significant risk of fishery collapse may develop as the capacity of fisheries to resist the following is exceeded: a) fundamental change to fishery composition, and b) the increased migration of disease and other organisms. (Sections 6.5.3, 7.5.1.1.3)
		Coastal ecosystems and communities that might be exposed to phenomena of elevated rates of microbial respiration leading to reduced oxygen at depth and increased spread of dead zones are particularly vulnerable (particularly for EBUE, SES, EUS).	Risk of loss of habitats and fishery resources as well as losses of key fisheries species. Oxygen levels decrease, leading to impacts on ecosystems (e.g., loss of habitat) and organisms (e.g., physiological performance of fish) resulting in reduced capture of key fisheries species.	Increasing risk of loss of livelihoods
		Deep sea life is sensitive to hazards and to change given the very constant conditions under which it has evolved. (30.1.3.1.3, 30.5.2, 30.5.5)	Risk of fundamental changes in conditions associated with deep sea (e.g., oxygen, pH, carbonate, CO_2, temperature) drive fundamental changes that result in broad-scale changes throughout the ocean. (Sections 30.1.3.1.3, 30.5.2, 30.5.5; Boxes CC-UP, CC-NPP)	Changes in the deep ocean may be a prelude to ocean wide changes with planetary implications.
	Rising ocean acidification	Reef systems, corals, and coastal ecosystems that are exposed to a reduced rate of calcification and greater decalcification leading to potential loss of carbonate reef systems, corals, molluscs, and other calcifiers in key regions, such as the CBS, STG (Section 6.2.2.2)	Risk of the alteration of ecosystem services including risks to food provisioning with impacts on fisheries and aquaculture (Sections 6.2.5.3, 7.2.1.2, 7.3.2, 7.4.2,)	Income and livelihoods for communities are reduced as productivity of fisheries and aquaculture diminish. (Sections 7.5.1.1.3, 30.6)
		Marine organisms that are susceptible to changes in pH and carbonate chemistry imply a large number of changes to the physiology and ecology of marine organisms (particularly in CBS, STG, SES regions). (Sections 6.2.5, 6.3.4, 30.3.2.2)	Risk of fundamental shifts in ecosystems composition as well as organism function occur, leading to broad scale and fundamental change. Income and livelihoods from dependent communities are affected as ecosystem goods and services decline, with the prospect that recovery may take tens of thousands of years. (Section 6.1.1.2)	Risk to ecosystems and livelihoods is increased by the potential for interaction among ocean warming and acidification to create unknown impacts. (Section CC-OA)
		Coastal systems are increasingly exposed to upwelling in some areas, which results in periods of high CO_2, low O_2 and pH. (Box CC-UP; Sections 6.2.2.2, 6.2.5.3)	Risk of loss and harm to fishery and aquaculture operations and respective livelihoods (e.g., oyster cultivation), especially those exposed periodically to harmful conditions during elevated upwelling, which trigger adaptation responses. (Section 30.6.2.1.4)	Background pH and carbonate chemistry are also such that harmful conditions are always present (avoiding impacts via adaptation not possible any more). (Section 30.6.2.1.4)
	Increased stratification as a result of ocean warming; reduced ventilation	Ocean ecosystems are vulnerable due to the reduced regeneration of nutrients as mixing between the ocean and its surface is reduced (EUS, STG, and EBUE). (Sections 6.2, 6.3, 6.5, 30.5.2, 30.5.4, 30.5.5)	Risk of productivity losses of oceans and respective negative impacts on fisheries. The concentration of inorganic nutrients in the upper layers of the ocean is reduced, leading to lower rates of primary productivity. (Box CC-NPP)	Reduced primary productivity of the ocean impacts fisheries productivity leading to lower catch rates and effects on livelihoods (Section 6.4.1.1; Box CC-NPP)
		Ecosystems and organisms that are sensitive to decreasing oxygen levels (Sections 30.5.2, 30.5.3, 30.5.5, 30.5.6, 30.5.7)	Increased risk of dead (hypoxic) zones reducing key ecosystems and fisheries habitat (Sections 6.1.1.3, 30.3.2.3)	
	Changes to wind, wave height, and storm intensity	Shipping and industrial infrastructure is vulnerable to wave and storm intensity. (Section 30.6.2)	Risk of increasing losses and damages to shipping and industrial infrastructure	Risk of accidents increases for enterprises such as shipping, as well as deep sea oil gas and mineral extraction.

CBS = Coastal Boundary Systems; EBUE = Eastern Boundary Upwelling Ecosystems; EUS = Equatorial Upwelling Systems; HIC, LIC, MIC = high-, low-, and medium-income countries; HLSBS = High-Latitude Spring Bloom Systems; SES = Semi-Enclosed Seas; STG = Sub-Tropical Gyres.

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KR

MB

Observed Global Responses of Marine Biogeography, Abundance, and Phenology to Climate Change

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IPCC WGII AR4 presented the detection of a global fingerprint on natural systems and its attribution to climate change (AR4, Chapter 1, SPM Figure 1), but studies from marine systems were mostly absent. Since AR4, there has been a rapid increase in studies that focus on climate change impacts on marine species, which represents an opportunity to move from more anecdotal evidence to examining and potentially attributing detected biological changes within the ocean to climate change (Section 6.3; Figure MB-1). Recent changes in populations of marine species and the associated shifts in diversity patterns are resulting, at least partly, from climate change–mediated biological responses across ocean regions (*robust evidence*, *high agreement*, *high confidence*; Sections 6.2, 30.5; Table 6-7).

Poloczanska et al. (2013) assess a potential pattern in responses of ocean life to recent climate change using a global database of 208 peer-reviewed papers. Observed responses (n = 1735) were recorded from 857 species or assemblages across regions and taxonomic groups, from phytoplankton to marine reptiles and mammals (Figure MB-1). Observations were defined as those where the authors of a particular paper assessed the change in a biological parameter (including distribution, phenology, abundance, demography, or community composition) and, if change occurred, the consistency of the change with that expected under climate change. Studies from the peer-reviewed literature were selected using three criteria: (1) authors inferred or directly tested for trends in biological and climatic variables; (2) authors included data after 1990; and (3) observations spanned at least 19 years, to reduce bias resulting from biological responses to short-term climate variability.

The results of this meta-analysis show that climate change has already had widespread impacts on species' distribution, abundance, phenology, and subsequently, species richness and community composition across a broad range of taxonomic groups (plankton to top predators). Of the observations that showed a response in either direction, changes in phenology, distribution and abundance were overwhelmingly (81%) in a direction that was consistent with theoretical responses to climate change (Section 6.2). Knowledge gaps exist, especially in equatorial sub-regions and the Southern Hemisphere (Figure MB-1).

The timing of many biological events (phenology) had an earlier onset. For example, over the last 50 years, spring events shifted earlier for many species with an average advancement of 4.4 ± 0.7 days per decade (mean ± SE) and summer events by 4.4 ± 1.1 days per decade (*robust evidence, high agreement, high confidence*) (Figure MB-2). Phenological observations included in the study range from shifts in peak abundance of phytoplankton and zooplankton, to reproduction and migration of invertebrates, fishes, and seabirds (Sections 6.3.2, 30.5).

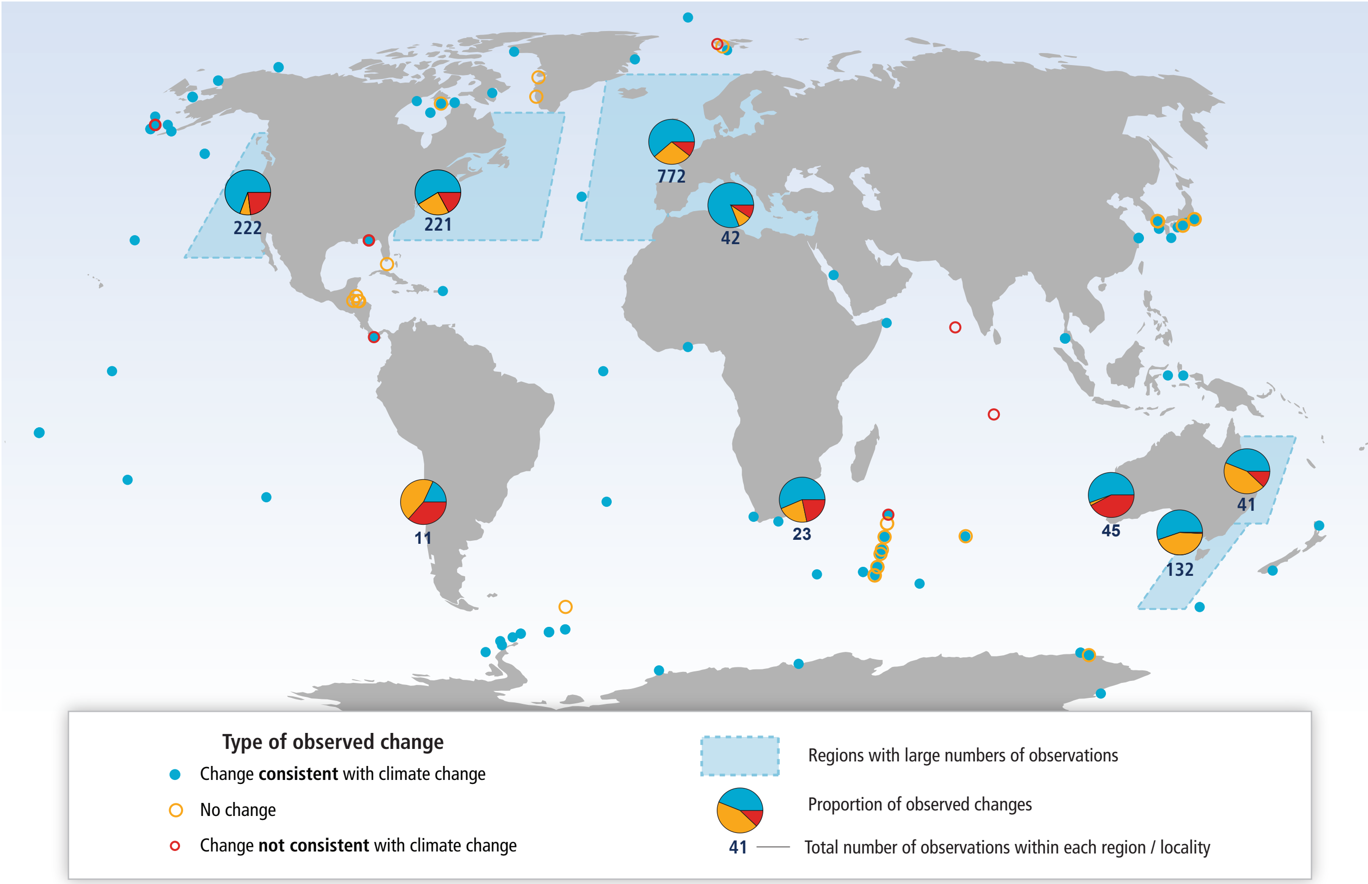

Figure MB-1 | 1735 observed responses to climate change from 208 single- and multi-species studies. Data shown include changes that are attributed (at least partly) to climate change (blue), changes that are inconsistent with climate change (red), and no change (orange). Each circle represents the center of a study area. Where points fall on land, it is because they are centroids of distributions that surround an island or peninsula. Studies encompass areas from single sites (e.g., seabird breeding colony) to large ocean regions (e.g., continuous plankton recorder surveys in north-east Atlantic). For regions (indicated by blue shading) and localities with large numbers of observations, pie charts summarize the relative proportions of the three types of observed changes (consistent with climate change, inconsistent with climate change, and no change) in those regions or localities. The numbers indicate the total observations within each region or locality. Note: 57% of the studies included were published since AR4. (From Poloczanska et al., 2013).

The distributions of benthic, pelagic, and demersal species and communities have shifted by up to a thousand kilometers, although the range shifts have not been uniform across taxonomic groups or ocean regions (Sections 6.3.2, 30.5) (*robust evidence, high agreement, high confidence*). Overall, leading range edges expanded in a poleward direction at 72.0 ± 13.5 km per decade and trailing edges contracted in a poleward direction at 15.8 ± 8.7 km per decade (Figure MB-2), revealing much higher current rates of migration than the potential maximum rates reported for terrestrial species (Figure 4-6) despite slower warming of the ocean than land surface (WGI Section 3.2).

Poleward distribution shifts have resulted in increased species richness in mid- to high-latitude regions (Hiddink and ter Hofstede, 2008) and changing community structure (Simpson et al., 2011; see also Section 28.2.2). Increases in warm-water components of communities concurrent with regional warming have been observed in mid- to high-latitude ocean regions including the Bering Sea, Barents Sea, Nordic Sea, North Sea, and Tasman Sea (Box 6.1; Section 30.5). Observed changes in species composition of catches from 1970–2006 that are partly attributed to long-term ocean warming suggest increasing dominance of warmer water species in subtropical and higher latitude regions, and reduction in abundance of subtropical species in equatorial waters (Cheung et al., 2013), with implications for fisheries (Sections 6.5, 7.4.2, 30.6.2.1).

The magnitude and direction of distribution shifts can be related to temperature velocities (i.e., the speed and direction at which isotherms propagate across the ocean's surface (Section 30.3.1.1; Burrows et al., 2011). Pinsky et al. (2013) showed that shifts in both latitude and depth of benthic fish and crustaceans could be explained by climate velocity with remarkable accuracy, using a database of 128 million individuals across 360 marine taxa from surveys of North American coastal waters conducted over 1968–2011. Poloczanska et al. (2013) found that faster distribution shifts generally occur in regions of highest surface temperature velocity, such as the North Sea and sub-Arctic Pacific Ocean. Observed marine species shifts, since approximately the 1950s, have generally been able to track observed velocities (Figure MB-3), with phyto- and zooplankton distribution shifts vastly exceeding climate velocities observed over most of the ocean surface, but with considerable variability within and among taxonomic groups (Poloczanska et al., 2013).

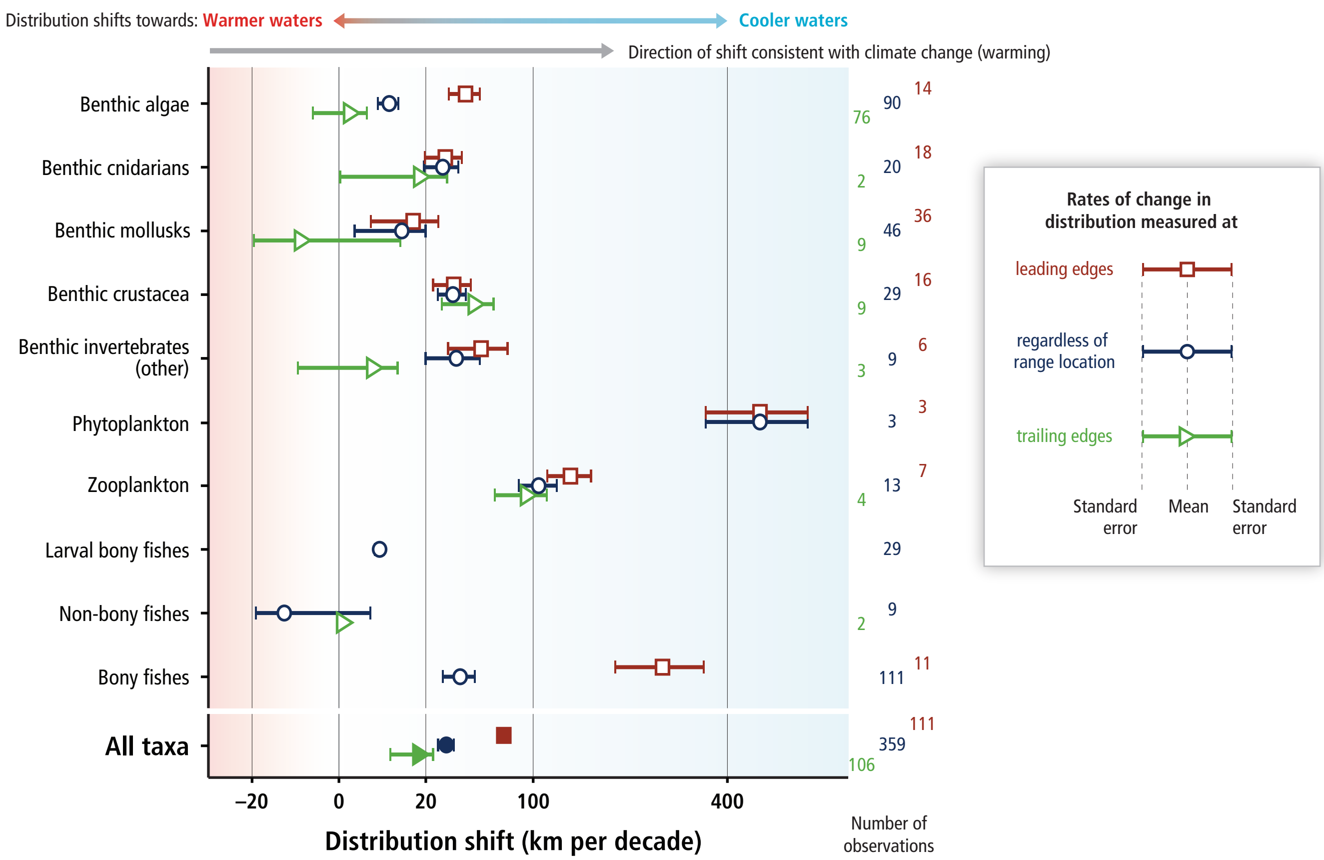

Figure MB-2 | Rates of change in distribution (kilometers per decade) for marine taxonomic groups, measured at the leading edges (red) and trailing edges (green). Average distribution shifts were calculated using all data, regardless of range location, and are in dark blue. Distribution shifts have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward). Means ± standard error are shown, along with number of observations. Non-bony fishes include sharks, rays, lampreys, and hagfish. (From Poloczanska et al., 2013).

Biogeographic shifts are also influenced by other factors such as currents, nutrient and stratification changes, light levels, sea ice, species' interactions, habitat availability and fishing, some of which can be independently influenced by climate change (Section 6.3). Rate and pattern of biogeographic shifts in sedentary organisms and benthic macroalgae are complicated by the influence of local dynamics and topographic features (islands, channels, coastal lagoons, e.g., of the Mediterranean (Bianchi, 2007), coastal upwelling e.g., (Lima et al., 2007)). Geographical barriers constrain range shifts and may cause a loss of endemic species (Ben Rais Lasram et al., 2010), with associated niches filled by alien species, either naturally migrating or artificially introduced (Philippart et al., 2011).

Whether marine species can continue to keep pace as rates of warming, hence climate velocities, increase (Figure MB-3b) is a key uncertainty. Climate velocities on land are expected to outpace the ability of many terrestrial species to track climate velocities this century (Section 4.3.2.5; Figure 4-6). For marine species, the observed rates of shift are generally much faster than those for land species, particularly for primary producers and lower trophic levels (Poloczanska et al., 2013). Phyto- and zooplankton communities (excluding larval fish) have extended distributions at remarkable rates (Figure MB-3b), such as in the Northeast Atlantic (Section 30.5.1) with implications for marine food webs.

Geographical range shifts and depth distribution vary between coexisting marine species (Genner et al., 2004; Perry et al., 2005; Simpson et al., 2011) as a consequence of the width of species-specific thermal windows and associated vulnerabilities (Figure 6-5). Warming therefore causes differential changes in growth, reproductive success, larval output, early juvenile survival, and recruitment, implying shifts in the relative performance of animal species and, thus, their competitiveness (Pörtner and Farrell, 2008; Figure 6-7A). Such effects may underlie abundance losses or local extinctions, "regime shifts" between coexisting species, or critical mismatches between predator and prey organisms, resulting in changes in local and regional species richness, abundance, community composition, productivity, energy flows, and invasion resistance. Even among Antarctic stenotherms, differences in biological responses related to mode of life, phylogeny and associated metabolic capacities exist (Section 6.3.1.4). As a consequence, marine ecosystem functions may be substantially reorganized at the regional scale, potentially triggering a range of cascading effects (Hoegh-Guldberg and Bruno, 2010). A focus on understanding the mechanisms underpinning the nature and magnitude of responses of marine organisms to climate change can help forecast impacts and the associated costs to society as well as facilitate adaptive management strategies formitigating these impacts (Sections 6.3, 6.4).

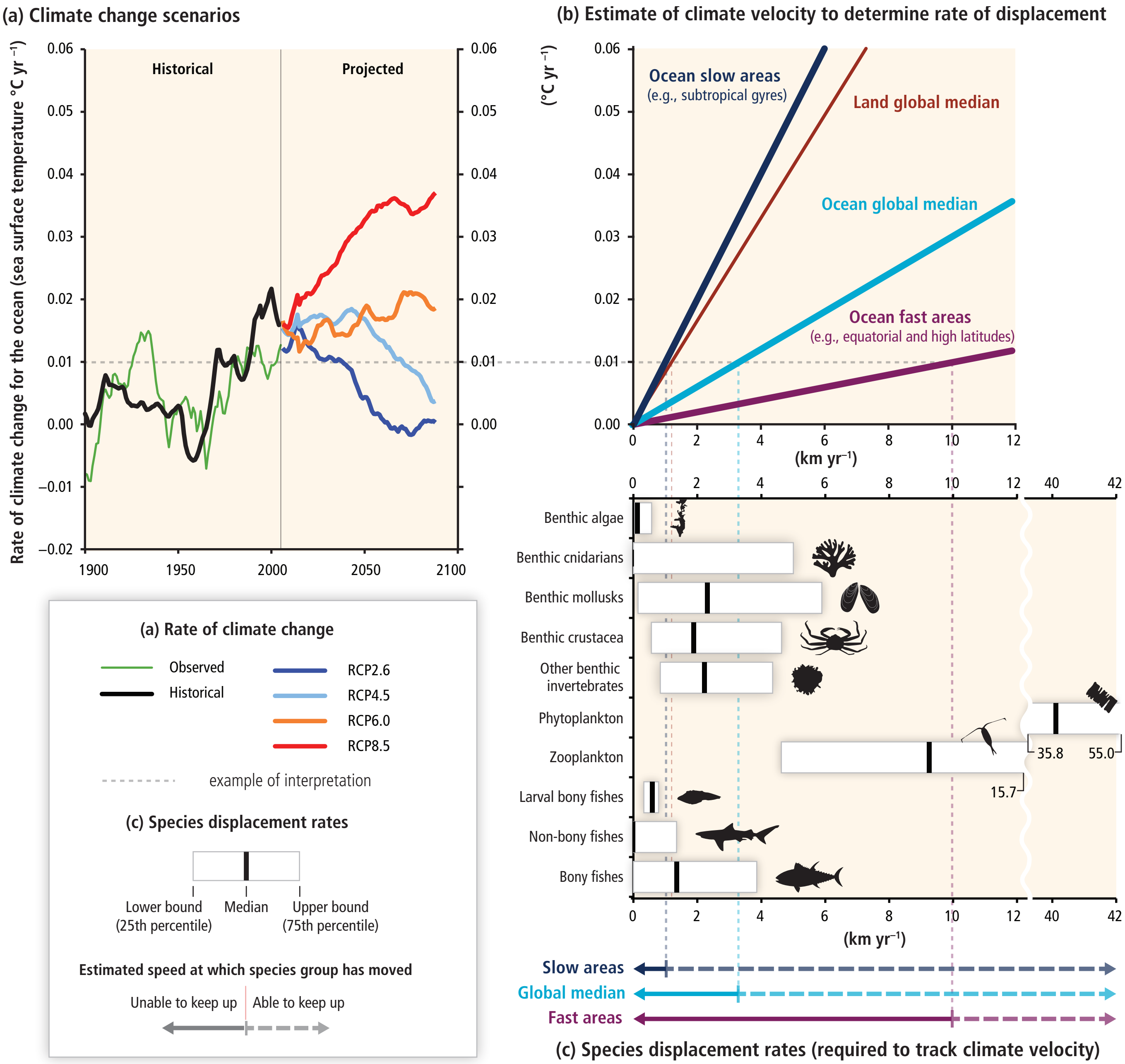

Figure MB-3 | (a) Rate of climate change for the ocean (sea surface temperature (SST) °C yr⁻¹). (b) Corresponding climate velocities for the ocean and median velocity from land (adapted from Burrows et al., 2011). (c) Observed rates of displacement of marine taxonomic groups based on observations over 1900–2010. The dotted bands give an example of interpretation. Rates of climate change of 0.01 °C yr⁻¹ correspond to approximately 3.3 km yr⁻¹ median climate velocity in the ocean. When compared to observed rates of displacement (c), many marine taxonomic groups have been able to track these velocities. For phytoplankton and zooplankton the rates of displacement greatly exceed median climate velocity for the ocean and, for phytoplankton exceed velocities in fast areas of the ocean approximately 10.0 km yr⁻¹. All values are calculated for ocean surface with the exclusion of polar seas (Figure 30-1a). (a) Observed rates of climate change for ocean SST (green line) are derived from the Hadley Centre Interpolated SST 1.1 (HadISST1.1) data set, and all other rates are calculated based on the average of the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model ensembles (Table SM30-3) for the historical period and for the future based on the four Representative Concentration Pathway (RCP) scenarios. Data were smoothed using a 20-year sliding window. (b) Median climate velocity over the global ocean surface (light blue line; excluding polar seas) calculated from HadSST1.1 data set over 1960–2009 using the methods of Burrows et al. (2011). Median velocities representative of ocean regions of slow velocities such as the Pacific subtropical gyre (dark blue line) and of high velocities such as the Coral Triangle or the North Sea (purple line) shown. Median rates over global land surface (red line) over 1960–2009 calculated using Climate Research Unit data set CRU TS3.1. Figure 30-3 shows climate velocities over the ocean surface calculated over 1960–2009. (c) Rates of displacement for marine taxonomic groups estimated by Poloczanska et al. (2013) using published studies. Note the displacement rates for phytoplankton exceed the axis, so values are given.

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OA

Ocean Acidification

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Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Figure OA-1A; WGI, Section 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulfur all exacerbate ocean acidification locally (Sections 5.3.3.6, 6.1.1, 30.3.2.2).

Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence, high agreement*). Increasing atmospheric concentrations of CO_2 result in an increased flux of CO_2 into a mildly alkaline ocean, resulting in a reduction in pH, carbonate ion concentration, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of the surface layers of the open ocean can be projected at the global scale with high accuracy using projections of atmospheric CO_2 levels (Figure CC-OA-1B). Observations of changing upper ocean CO_2 chemistry over time support this linkage (WGI Table 3.2 and Figure 3.18; Figures 30-8, 30-9). Projected changes in open ocean, surface water chemistry for the year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to pre-industrial values range from a pH change of –0.14 units with Representative Concentration Pathway (RCP)2.6 (421 ppm CO_2, +1°C, 22% reduction of carbonate ion concentration) to a pH change of –0.43 units with RCP8.5 (936 ppm CO_2, +3.7°C, 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (Sections 5.3.3.5, 30.3.2.2), in polar regions (WGI Section 6.4.4), and at depth are more difficult but generally follow similar trends.

Biological, Ecological, and Biogeochemical Impacts

Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, recently analyzed in several meta-analyses (Sections 6.3.2.1, 6.3.5.1). A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms, with a trend for greater sensitivity in early life stages (*high confidence*; Sections 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Figure OA-1C) but key uncertainties remain in our understanding of the impacts on organisms, life histories, and ecosystems. Responses can be influenced, often exacerbated by other drivers, such as warming, hypoxia, nutrient concentration, and light availability (*high confidence*; Sections 5.4.2.4, 6.3.5).

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; Sections 5.4.2.3, 6.3.2.2, 6.3.2.3, 30.5.6). Harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may stimulate nitrogen fixation (*limited evidence, low agreement*; 6.3.2.2). It decreases the rate of calcification of most, but not all, sea floor calcifiers (*medium agreement, robust evidence*) such as reef-building corals (Box CC-CR), coralline algae, bivalves, and gastropods, reducing the competitiveness with non-calcifiers (Sections 5.4.2.2, 5.4.2.4, 6.3.2.5). Ocean warming and acidification promote higher rates of calcium carbonate dissolution resulting in the net dissolution of carbonate sediments and frameworks and loss of associated habitat (*medium confidence*; 5.4.2.4, 6.3.2.5, 6.3.5.4). Some corals and temperate fishes experience disturbances to behavior, navigation, and their ability to tell conspecifics from predators (Section 6.3.2.4). However, there is no evidence for these effects to persist on evolutionary time scales in the few groups analyzed (Section 6.3.2).

Some phytoplankton and molluscs displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; Section 6.3.2.1), indicating that the long-term responses could be less than responses obtained in short-term experiments. However, mass extinctions in Earth history occurred during much slower rates of ocean acidification, combined with other drivers changing, suggesting that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of future change (*medium confidence*; Section 6.1.2).

Projections of ocean acidification effects at the ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution will change predator–prey relationships and competitive interactions (Sections

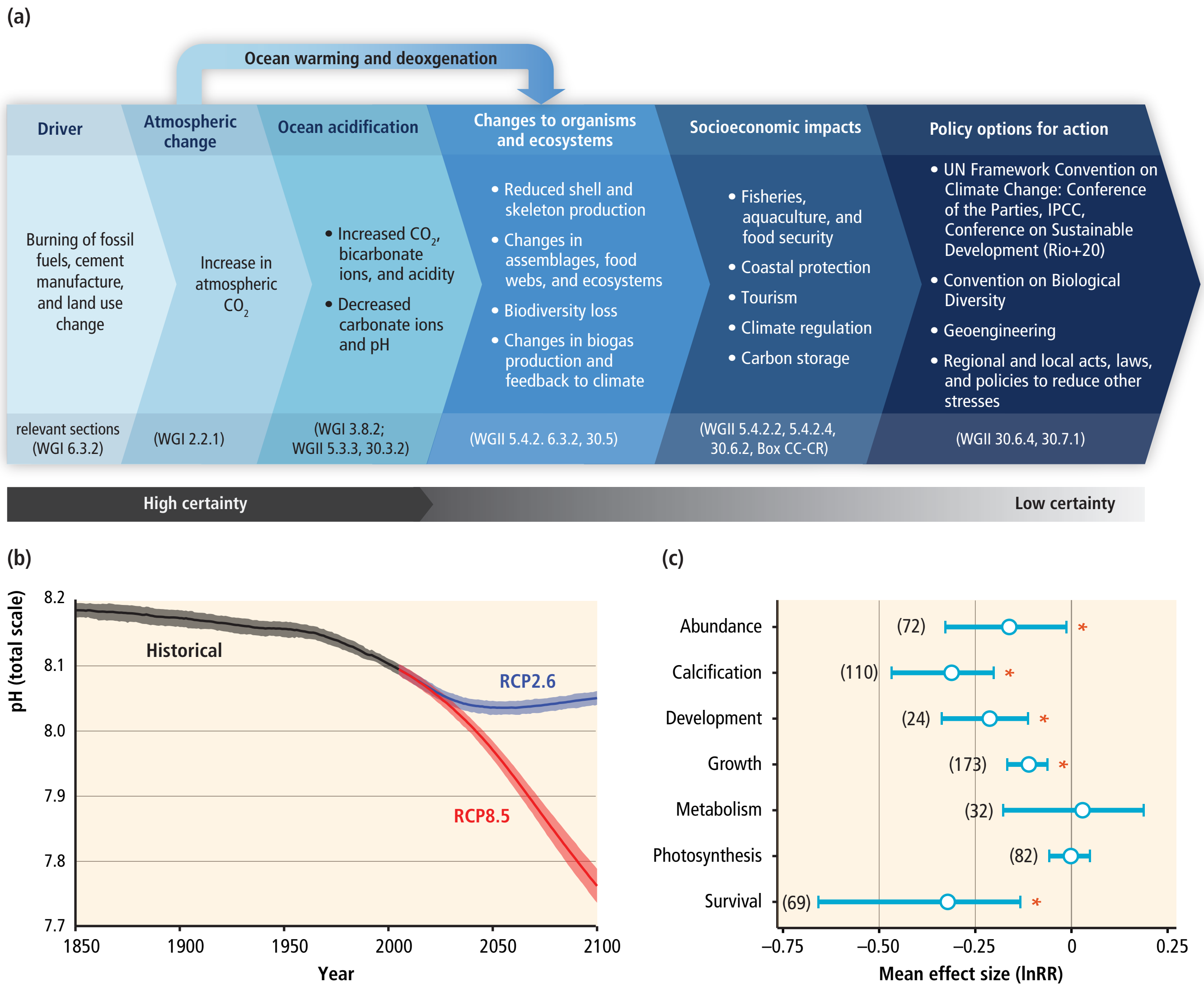

Figure OA-1 | (a) Overview of the chemical, biological, and socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). (b) Multi-model simulated time series of global mean ocean surface pH (on the total scale) from Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model simulations from 1850 to 2100. Projections are shown for emission scenarios Representative Concentration Pathway (RCP)2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (gray shading) is the modeled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations (WGI AR5 Figures SPM.7 and TS.20). (c) Effect of near-future acidification (seawater pH reduction of ≤0.5 units) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival, which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (lnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification, but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. The * denotes a statistically significant effect.

6.3.2.5, 6.3.5, 6.3.6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO_2 vents indicate decreased species diversity, biomass, and trophic complexity of communities (Box CC-CR; Sections 5.4.2.3, 6.3.2.5, 30.3.2.2, 30.5). Shifts in community structure have also been documented in regions with rapidly declining pH (Section 5.4.2.2).

Owing to an incomplete understanding of species-specific responses and trophic interactions, the effect of ocean acidification on global biogeochemical cycles is not well understood (*limited evidence, low agreement*) and represents an important knowledge gap. The additive, synergistic, or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not sufficiently investigated yet.

Risks, Socioeconomic Impacts, and Costs

The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, include both the probability that ocean acidification will affect fundamental physiological and ecological processes of organisms (Section 6.3.2.1), and the magnitude of the resulting impacts on ecosystems and the ecosystem services they provide to society (Box 19-2). For example, ocean acidification under RCP4.5 to RCP8.5 will impact formation and maintenance of coral reefs (*high confidence*; Box CC-CR, Section 5.4.2.4) and the goods and services that they provide such as fisheries, tourism, and coastal protection (*limited evidence, high agreement*; Box CC-CR; Sections 6.4.1.1,19.5.2, 27.3.3, 30.5, 30.6). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed because of the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (Section 19.5.2).

Global estimates of observed or projected economic costs of ocean acidification do not exist. The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. However, there are a number of instructive examples that illustrate the magnitude of potential impacts of ocean acidification. A decrease of the production of commercially exploited shelled molluscs (Section 6.4.1.1) would result in a reduction of USA production of 3 to 13% according to the Special Report on Emission Scenarios (SRES) A1FI emission scenario (*low confidence*). The global cost of production loss of molluscs could be more than US$100 billion by 2100 (*limited evidence, medium agreement*). Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and that complex additive, antagonistic, and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (Section 6.4.1.1). The annual economic damage of ocean-acidification–induced coral reef loss by 2100 has been estimated, in 2012, to be US$870 and 528 billion, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; Section 6.4.1). Although this number is small compared to global gross domestic product (GDP), it can represent a very large GDP loss for the economies of many coastal regions or small islands that rely on the ecological goods and services of coral reefs (Sections 25.7.5, 29.3.1.2).

Mitigation and Adaptation

Successful management of the impacts of ocean acidification includes two approaches: mitigation of the source of the problem (i.e., reduce anthropogenic emissions of CO_2) and/or adaptation by reducing the consequences of past and future ocean acidification (Section 6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts (Section 6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could increase it under some circumstances (Section 6.4.2.2). Geoengineering techniques to remove CO_2 from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO_2 storage capacity (Section 6.4.2.2). In addition, some ocean-based approaches, such as iron fertilization, would only relocate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep water oxygen levels (Sections 6.4.2.2, 30.3.2.3, 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO_2, such as nutrient pollution (Section 6.4.2.1). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (Section 5.3.4.2). Some adaptation strategies include drawing water for aquaculture from local watersheds only when pH is in the right range, selecting for less sensitive species or strains, or relocating industries elsewhere (Section 6.4.2.1).

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PP

Net Primary Production in the Ocean

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Net Primary Production (NPP) is the rate of photosynthetic carbon fixation minus the fraction of fixed carbon used for cellular respiration and maintenance by autotrophic planktonic microbes and benthic plants (Sections 6.2.1, 6.3.1). Environmental drivers of NPP include light, nutrients, micronutrients, CO_2, and temperature (Figure PP-1a). These drivers, in turn, are influenced by oceanic and atmospheric processes, including cloud cover; sea ice extent; mixing by winds, waves, and currents; convection; density stratification; and various forms of upwelling induced by eddies, frontal activity, and boundary currents. Temperature has multiple roles as it influences rates of phytoplankton physiology and heterotrophic bacterial recycling of nutrients, in addition to stratification of the water column and sea ice extent (Figure PP-1a). Climate change is projected to strongly impact NPP through a multitude of ways that depend on the regional and local physical settings (WGI AR5, Chapter 3), and on ecosystem structure and functioning (*medium confidence*; Sections 6.3.4, 6.5.1). The influence of environmental drivers on NPP causes as much as a 10-fold variation in regional productivity with nutrient-poor subtropical waters and light-limited Arctic waters at the lower range and productive upwelling regions and highly eutrophic coastal regions at the upper range (Figure PP-1b).

The oceans currently provide ~50×10^{15} g C yr^{-1}, or about half of global NPP (Field et al., 1998). Global estimates of NPP are obtained mainly from satellite remote sensing (Section 6.1.2), which provides unprecedented spatial and temporal coverage, and may be validated regionally against oceanic measurements. Observations reveal significant changes in rates of NPP when environmental controls are altered by episodic natural perturbations, such as volcanic eruptions enhancing iron supply, as observed in high-nitrate low-chlorophyll waters of the Northeast Pacific (Hamme et al., 2010). Climate variability can drive pronounced changes in NPP (Chavez et al., 2011), such as from El Niño to La Niña transitions in Equatorial Pacific, when vertical nutrient and trace element supply are enhanced (Chavez et al., 1999).

Multi-year time series records of NPP have been used to assess spatial trends in NPP in recent decades. Behrenfeld et al. (2006), using satellite data, reported a prolonged and sustained global NPP decrease of 190×10^{12} g C yr^{-1}, for the period 1999–2005—an annual reduction of 0.57% of global NPP. In contrast, a time series of directly measured NPP between 1988 and 2007 by Saba et al. (2010) (i.e., *in situ* incubations using the radiotracer ^{14}C-bicarbonate) revealed an increase (2% yr^{-1}) in NPP for two low-latitude open ocean sites. This discrepancy between *in situ* and remotely sensed NPP trends points to uncertainties in either the methodology used and/or the extent to which discrete sites are representative of oceanic provinces (Saba et al., 2010, 2011). Modeling studies have subsequently revealed that the <15-year archive of satellite-

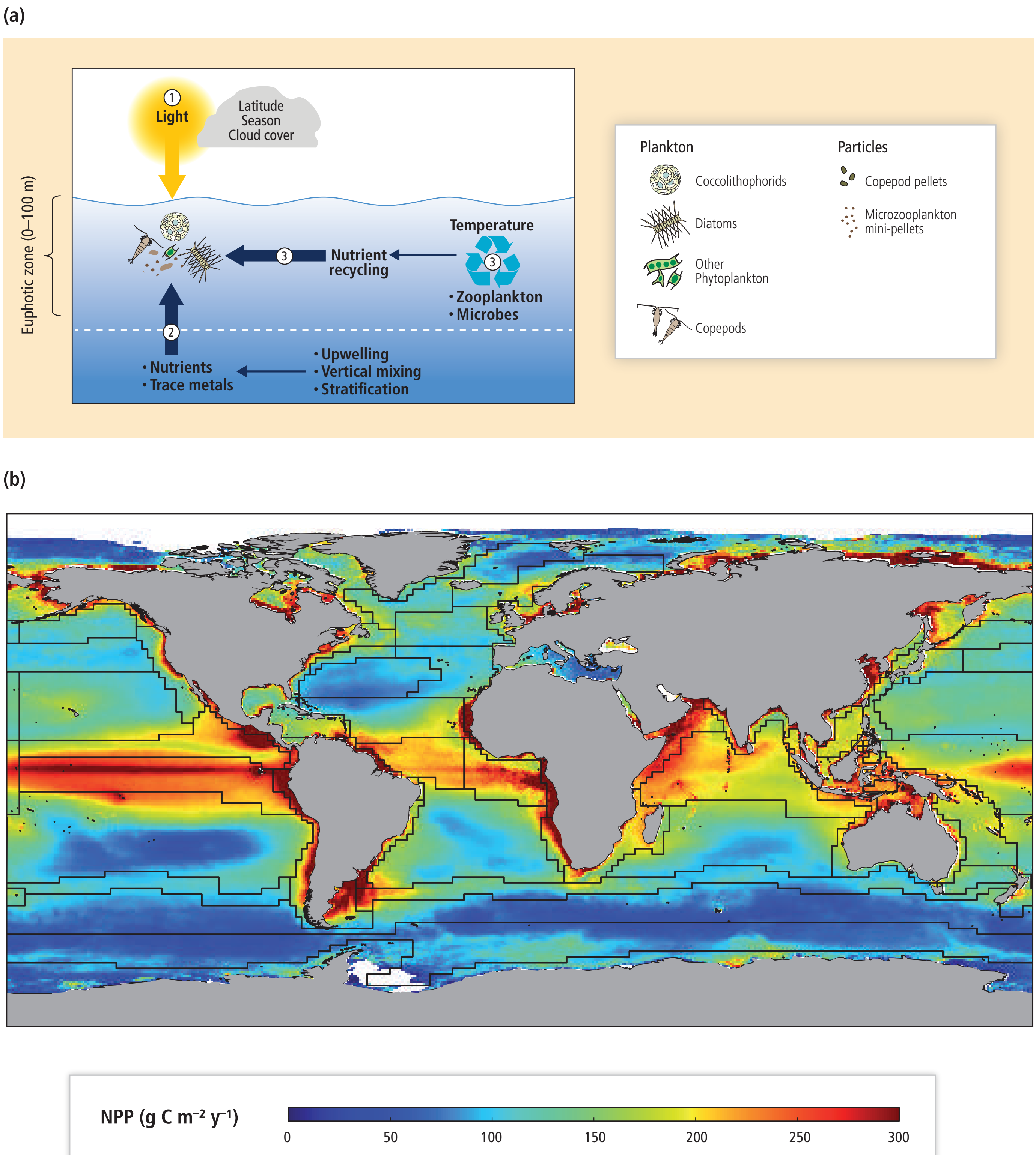

Figure PP-1 | (a) Environmental factors controlling Net Primary Production (NPP). NPP is controlled mainly by three basic processes: (1) light conditions in the surface ocean, that is, the photic zone where photosynthesis occurs; (2) upward flux of nutrients and micronutrients from underlying waters into the photic zone, and (3) regeneration of nutrients and micronutrients via the breakdown and recycling of organic material before it sinks out of the photic zone. All three processes are influenced by physical, chemical, and biological processes and vary across regional ecosystems. In addition, water temperature strongly influences the upper rate of photosynthesis for cells that are resource-replete. Predictions of alteration of primary productivity under climate change depend on correct parameterizations and simulations of each of these variables and processes for each region. (b) Annual composite map of global areal NPP rates (derived from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua satellite climatology from 2003–2012; NPP was calculated with the Carbon-based Productivity Model (CbPM; Westberry et al., 2008)). Overlaid is a grid of (thin black lines) that represent 51 distinct global ocean biogeographical provinces (after Longhurst, 1998 and based on Boyd and Doney, 2002). The characteristics and boundaries of each province are primarily set by the underlying regional ocean physics and chemistry. White areas = no data. (Figure courtesy of Toby Westberry (OSU) and Ivan Lima (WHOI), satellite data courtesy of NASA Ocean Biology Processing Group.)

derived NPP is insufficient to distinguish climate-change mediated shifts in NPP from those driven by natural climate variability (Henson et al., 2010; Beaulieu et al., 2013). Although multi-decadal, the available time series of oceanic NPP measurements are also not of sufficient duration relative to the time scales of longer-term climate variability modes as for example Atlantic Multi-decadal Oscillation (AMO), with periodicity of 60-70 years, Figure 6-1). Recent attempts to synthesize longer (i.e., centennial) records of chlorophyll as a proxy for phytoplankton stocks (e.g., Boyce et al., 2010) have been criticized for relying on questionable linkages between different proxies for chlorophyll over a century of records (e.g., Rykaczewski and Dunne, 2011).

Models in which projected climate change alters the environmental drivers of NPP provide estimates of spatial changes and of the rate of change of NPP. For example, four global coupled climate–ocean biogeochemical Earth System Models (WGI AR5 Chapter 6) projected an increase in NPP at high latitudes as a result of alleviation of light and temperature limitation of NPP, particularly in the high-latitude biomes (Steinacher et al., 2010). However, this regional increase in NPP was more than offset by decreases in NPP at lower latitudes and at mid-latitudes due to the reduced input of macronutrients into the photic zone. The reduced mixed-layer depth and reduced rate of circulation may cause a decrease in the flux of macronutrients to the euphotic zone (Figure 6-2). These changes to oceanic conditions result in a reduction in global mean NPP by 2 to 13% by 2100 relative to 2000 under a high emission scenario (Polovina et al., 2011; SRES (Special Report on Emission Scenarios) A2, between RCP6.0 and RCP8.5). This is consistent with a more recent analysis based on 10 Earth System Models (Bopp et al., 2013), which project decreases in global NPP by 8.6 (±7.9), 3.9 (±5.7), 3.6 (±5.7), and 2.0 (±4.1) % in the 2090s relative to the 1990s, under the scenarios RCP8.5, RCP6.0, RCP4.5, and RCP2.6, respectively. However, the magnitude of projected changes varies widely between models (e.g., from 0 to 20% decrease in NPP globally under RCP 8.5). The various models show very large differences in NPP at regional scales (i.e., provinces, see Figure PP-1b).

Model projections had predicted a range of changes in global NPP from an increase (relative to preindustrial rates) of up to 8.1% under an intermediate scenario (SRES A1B, similar to RCP6.0; Sarmiento et al., 2004; Schmittner et al., 2008) to a decrease of 2-20% under the SRES A2 emission scenario (Steinacher et al., 2010). These projections did not consider the potential contribution of primary production derived from atmospheric nitrogen fixation in tropical and subtropical regions, favoured by increasing stratification and reduced nutrient inputs from mixing. This mechanism is potentially important, although such episodic increases in nitrogen fixation are not sustainable without the presence of excess phosphate (e.g., Moore et al., 2009; Boyd et al., 2010). This may lead to an underestimation of NPP (Mohr et al., 2010; Mulholland et al., 2012; Wilson et al., 2012), however, the extent of such underestimation is unknown (Luo et al., 2012).

Care must be taken when comparing global, provincial (e.g., low-latitude waters, e.g., Behrenfeld et al., 2006) and regional trends in NPP derived from observations, as some regions have additional local environmental influences such as enhanced density stratification of the upper ocean from melting sea ice. For example, a longer phytoplankton growing season, due to more sea ice–free days, may have increased NPP (based on a regionally validated time-series of satellite NPP) in Arctic waters (Arrigo and van Dijken, 2011) by an average of 8.1×10^{12} g C yr^{-1} between 1998 and 2009. Other regional trends in NPP are reported in Sections 30.5.1 to 30.5.6. In addition, although future model projections of global NPP from different models (Steinacher et al., 2010; Bopp et al., 2013) are comparable, regional projections from each of the models differ substantially. This raises concerns as to which aspect(s) of the different model NPP parameterizations are responsible for driving regional differences in NPP, and moreover, how accurate model projections are of global NPP.

From a global perspective, open ocean NPP will decrease moderately by 2100 under both low- (SRES B1 or RCP4.5) and high-emission scenarios (*medium confidence*; SRES A2 or RCPs 6.0, 8.5, Sections 6.3.4, 6.5.1), paralleled by an increase in NPP at high latitudes and a decrease in the tropics (*medium confidence*). However, there is *limited evidence* and *low agreement* on the direction, magnitude and differences of a change of NPP in various ocean regions and coastal waters projected by 2100 (*low confidence*).

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RC

Regional Climate Summary Figures

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Information about the likelihood of regional climate change, assessed by Working Group I (WGI), is foundational for the Working Group II assessment of climate-related risks. To help communicate this assessment, the regional chapters of WGII present a coordinated set of regional climate figures, which summarize observed and projected change in annual average temperature and precipitation during the near term and the longer term for RCP2.6 and RCP8.5. These WGII regional climate summary figures use the same temperature and precipitation fields that are assessed in WGI Chapter 2 and WGI Chapter 12, with spatial boundaries, uncertainty metrics, and data classes tuned to support the WGII assessment of climate-related risks and options for risk management. Additional details on regional climate and regional climate processes can be found in WGI Chapter 14 and WGI Annex 1.

The WGII maps of observed annual temperature and precipitation use the same source data, calculations of data sufficiency, and calculations of trend significance as WGI Chapter 2 and WGI Figures SPM.1 and SPM.2. (A full description of the observational data selection and significance testing can be found in WGI Box 2.2.) Observed trends are determined by linear regression over the 1901–2012 period of Merged Land–Ocean Surface Temperature (MLOST) for annual temperature, and over the 1951–2010 period of Global Precipitation Climatology Centre (GPCC) for annual precipitation. Data points on the maps are classified into three categories, reflecting the categories used in WGI Figures SPM.1 and SPM.2:

1) Solid colors indicate areas where (a) sufficient data exist to permit a robust estimate of the trend (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period), and (b) the trend is significant at the 10% level (after accounting for autocorrelation effects on significance testing).
2) Diagonal lines indicate areas where sufficient data exist to permit a robust estimate of the trend, but the trend is not significant at the 10% level.
3) White indicates areas where there are not sufficient data to permit a robust estimate of the trend.

The WGII maps of projected annual temperature and precipitation are based on the climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012), which also form the basis for the figures presented in WGI (including WGI Chapters 12, 14, and Annex I). The CMIP5 archive includes output from Atmosphere–Ocean General Circulation Models (AOGCMs), AOGCMs with coupled vegetation and/or carbon cycle components, and AOGCMs with coupled atmospheric chemistry components. The number of models from which output is available, and the number of realizations of each model, vary between the different CMIP5 experiments. The WGII regional climate maps use the same source data as WGI Chapter 12 (e.g., Box 12.1 Figure

1), including the WGI multi-model mean values; the WGI individual model values; the WGI measure of baseline ("internal") variability; and the WGI time periods for the reference (1986–2005), mid-21st century (2046–2065), and late-21st century (2081–2100) periods. The full description of the selection of models, the selection of realizations, the definition of internal variability, and the interpolation to a common grid can be found in WGI Chapter 12 and Annex I.

In contrast to the Coupled Model Intercomparison Project Phase 3 (CMIP3) (Meehl et al., 2007), which used the IPCC Special Report on Emission Scenarios (SRES) emission scenarios (IPCC, 2000), CMIP5 uses the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011) to characterize possible trajectories of climate forcing over the 21st century. The WGII regional climate projection maps include RCP2.6 and RCP8.5, which represent the high and low end of the RCP range at the end of the 21st century. Projected changes in global mean temperature are similar across the RCPs over the next few decades (Figure RC-1; WGI Figure 12.5). During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate. In addition, societal responses, particularly adaptations, will influence near-term outcomes. In the second half of the 21st century and beyond, the magnitude of global temperature increase diverges across the RCPs (Figure RC-1; WGI Figure 12.5). For this longer-term era of climate options, near-term and longer-term mitigation and adaptation, as well as development pathways, will determine the risks of climate change. The benefits of mitigation and adaptation thereby occur over different but overlapping time frames, and present-day choices thus affect the risks of climate change throughout the 21st century.

The projection maps plot differences in annual average temperature and precipitation between the future and reference periods (Figures RC-2 and RC-3), categorized into four classes. The classes are constructed based on the IPCC uncertainty guidance, providing a quantitative basis for assigning likelihood (Mastrandrea et al., 2010), with *likely* defined as 66 to 100% and *very likely* defined as 90 to 100%.

RC

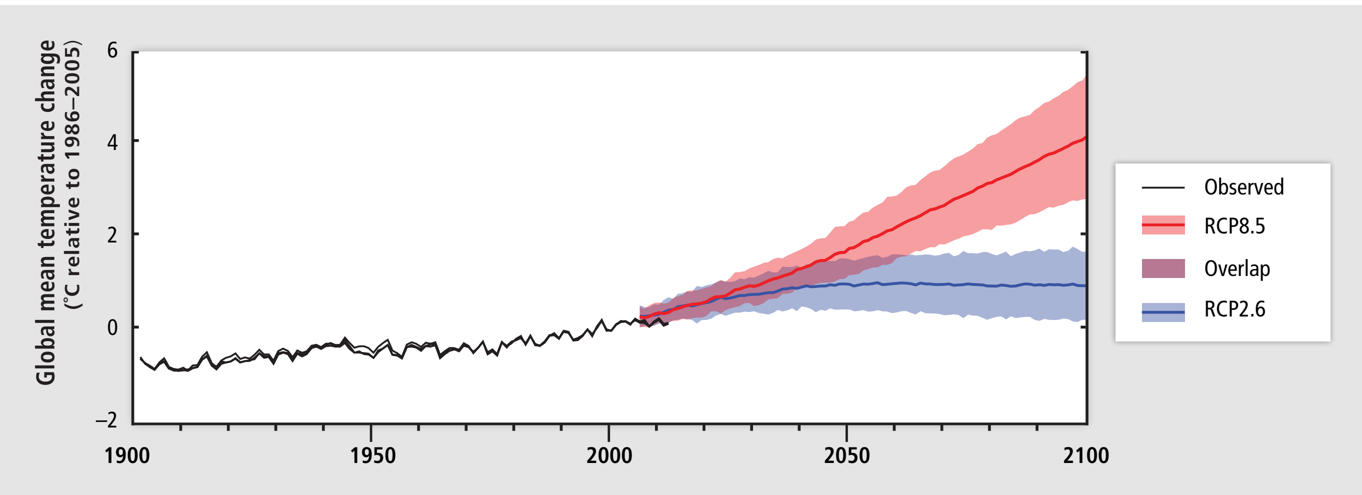

Figure RC-1 | Observed and projected changes in global annual average temperature. Values are expressed relative to 1986–2005. Black lines show the Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP), National Climate Data Center Merged Land–Ocean Surface Temperature (NCDC-MLOST), and Hadley Centre/Climatic Research Unit gridded surface temperature data set 4.2 (HadCRUT4.2) estimates from observational measurements. Blue and red lines and shading denote the ensemble mean and ±1.64 standard deviation range, based on Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations from 32 models for Representative Concentration Pathway (RCP) 2.6 and 39 models for RCP8.5.

The classifications in the WGII regional climate projection figures are based on two aspects of likelihood (e.g., WGI Box 12.1 and Knutti et al., 2010). The first is the likelihood that projected changes exceed differences arising from internal climate variability (e.g., Tebaldi et al., 2011). The second is agreement among models on the sign of change (e.g., Christensen et al., 2007; and IPCC, 2012).

The four classifications of projected change depicted in the WGII regional climate maps are:

1) Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-year means), and greater than or equal to 90% of models agree on sign of change. These criteria (and the areas that fall into this category) are identical to the highest confidence category in WGI Box 12.1. This category supersedes other categories in the WGII regional climate maps.
2) Colors with white dots indicate areas with strong agreement, where 66% or more of models show change greater than the baseline variability, and 66% or more of models agree on sign of change.
3) Gray indicates areas with divergent changes, where 66% or more of models show change greater than the baseline variability, but fewer than 66% agree on sign of change.
4) Colors with diagonal lines indicate areas with little or no change, where fewer than 66% of models show change greater than the baseline variability. It should be noted that areas that fall in this category for the annual average could still exhibit significant change at seasonal, monthly, and/or daily time scales.

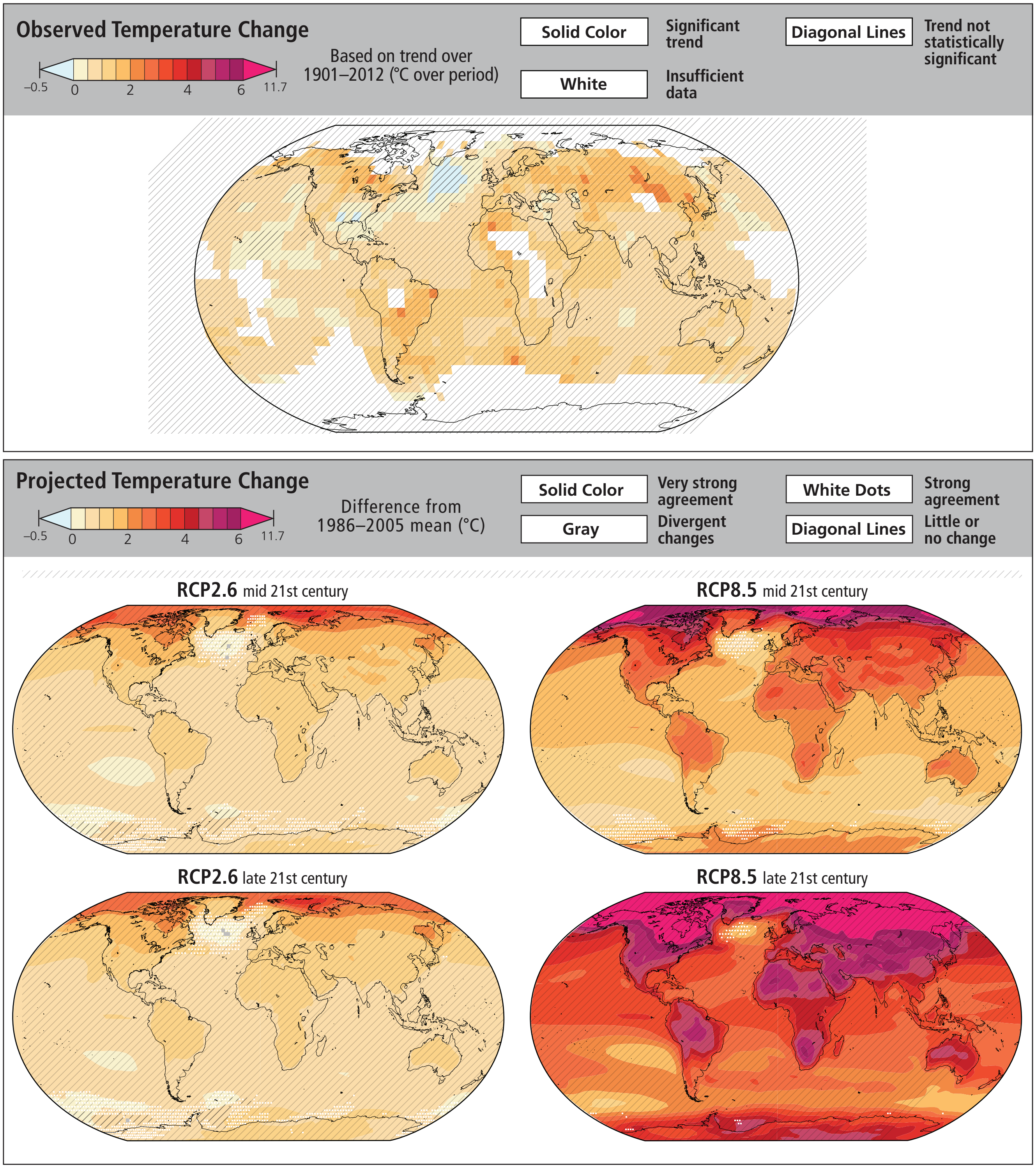

Figure RC-2 | Observed and projected changes in annual average surface temperature. (A) Map of observed annual average temperature change from 1901 to 2012, derived from a linear trend where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period); other areas are white. Solid colors indicate areas where trends are significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where trends are not significant. Observed data (range of grid-point values: –0.53 to +2.50°C over period) are from WGI AR5 Figures SPM.1 and 2.21. (B) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model mean projections of annual average temperature changes for 2046–2065 and 2081–2100 under Representative Concentration Pathway (RCP) 2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-year means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is: +0.19 to +4.08°C for mid 21st century of RCP2.6; +0.06 to +3.85°C for late 21st century of RCP2.6; +0.70 to +7.04°C for mid 21st century of RCP8.5; and +1.38 to +11.71°C for late 21st century of RCP8.5.

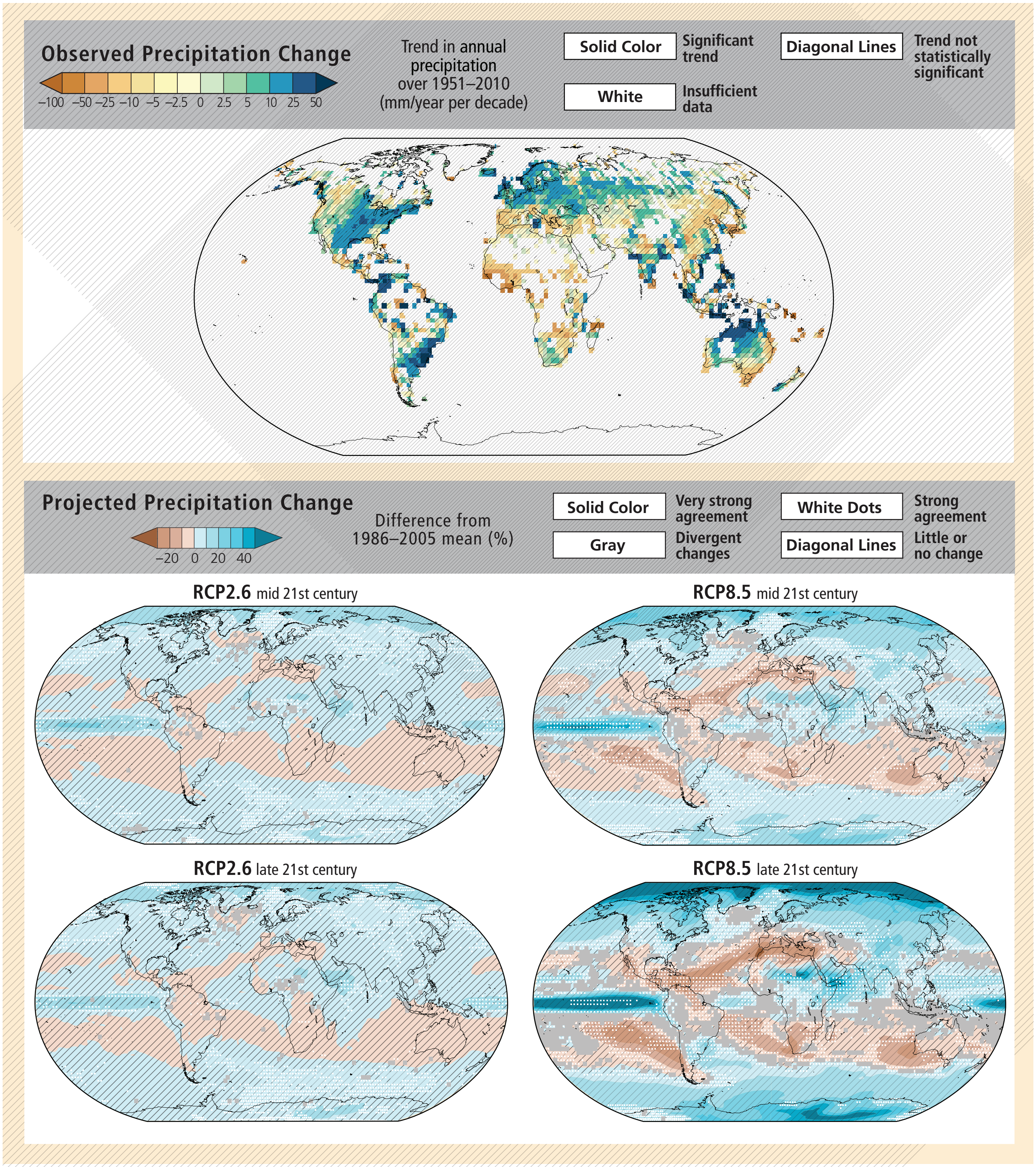

Figure RC-3 | Observed and projected changes in annual average precipitation. (A) Map of observed annual precipitation change from 1951–2010, derived from a linear trend where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period); other areas are white. Solid colors indicate areas where trends are significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where trends are not significant. Observed data (range of grid-point values: –185 to +111 mm/year per decade) are from WGI AR5 Figures SPM.2 and 2.29. (B) Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model average percent changes in annual mean precipitation for 2046–2065 and 2081–2100 under Representative Concentration Pathway (RCP) 2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is: –10 to +24% for mid 21st century of RCP2.6; –9 to +22% for late 21st century of RCP2.6; –19 to +57% for mid 21st century of RCP8.5; and –34 to +112% for late 21st century of RCP8.5.

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RF

Impact of Climate Change on Freshwater Ecosystems due to Altered River Flow Regimes

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It is widely acknowledged that the flow regime is a primary determinant of the structure and function of rivers and their associated floodplain wetlands, and flow alteration is considered to be a serious and continuing threat to freshwater ecosystems (Bunn and Arthington, 2002; Poff and Zimmerman, 2010; Poff et al., 2010). Most species distribution models do not consider the effect of changing flow regimes (i.e., changes to the frequency, magnitude, duration, and/or timing of key flow parameters) or they use precipitation as proxy for river flow (Heino et al., 2009).

There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (*medium confidence*; Xenopoulos et al., 2005; Aldous et al., 2011). By the 2050s, climate change is projected to impact river flow characteristics such as long-term average discharge, seasonality, and statistical high flows (but not statistical low flows) more strongly than dam construction and water withdrawals have done up to around the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario (Special Report on Emission Scenarios (SRES) A2 emissions, Met Office Hadley Centre climate prediction model 3 (HadCM3)), 15% of the global land area may be negatively affected, by the 2050s, by a decrease of fish species in the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change may exacerbate the negative impacts of dams for freshwater ecosystems but may also provide opportunities for operating dams and power stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, as occurs in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, that is, with a lower spring flood and increased runoff during winter months (Renofalt et al., 2010).

Because biota are often adapted to a certain level of river flow variability, the projected larger variability of river flows that is due to increased climate variability is *likely* to select for generalist or invasive species (Ficke et al., 2007). The relatively stable habitats of groundwater-fed streams in snow-dominated or glacierized basins may be altered by reduced recharge by meltwater and as a result experience more variable (possibly intermittent) flows (Hannah et al., 2007). A high-impact change of flow variability is a flow regime shift from intermittent to perennial or vice versa. It is projected that until the 2050s, river flow regime shifts may occur on 5 to 7% of the global land area, mainly in semiarid areas (Döll and Müller Schmied, 2012; see Table 3-2 in Chapter 3).

In Africa, one third of fish species and one fifth of the endemic fish species occur in eco-regions that may experience a change in discharge or runoff of more than 40% by the 2050s (Thieme et al., 2010). Eco-regions containing more than 80% of Africa's freshwater fish species and several outstanding ecological and evolutionary phenomena are *likely* to experience hydrologic conditions substantially different from the present, with alterations in long-term average annual river discharge or runoff of more than 10% due to climate change and water use (Thieme et al., 2010).

As a result of increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by higher river flows in winter, earlier spring peak flows, and possibly reduced summer low flows (Section 3.2.3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20 to 40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg incubation, the relatively pristine high-elevation areas being affected most (Battin et al., 2007). Reductions in summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart et al., 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release patterns will be an important adaptation strategy (Palmer et al., 2009).

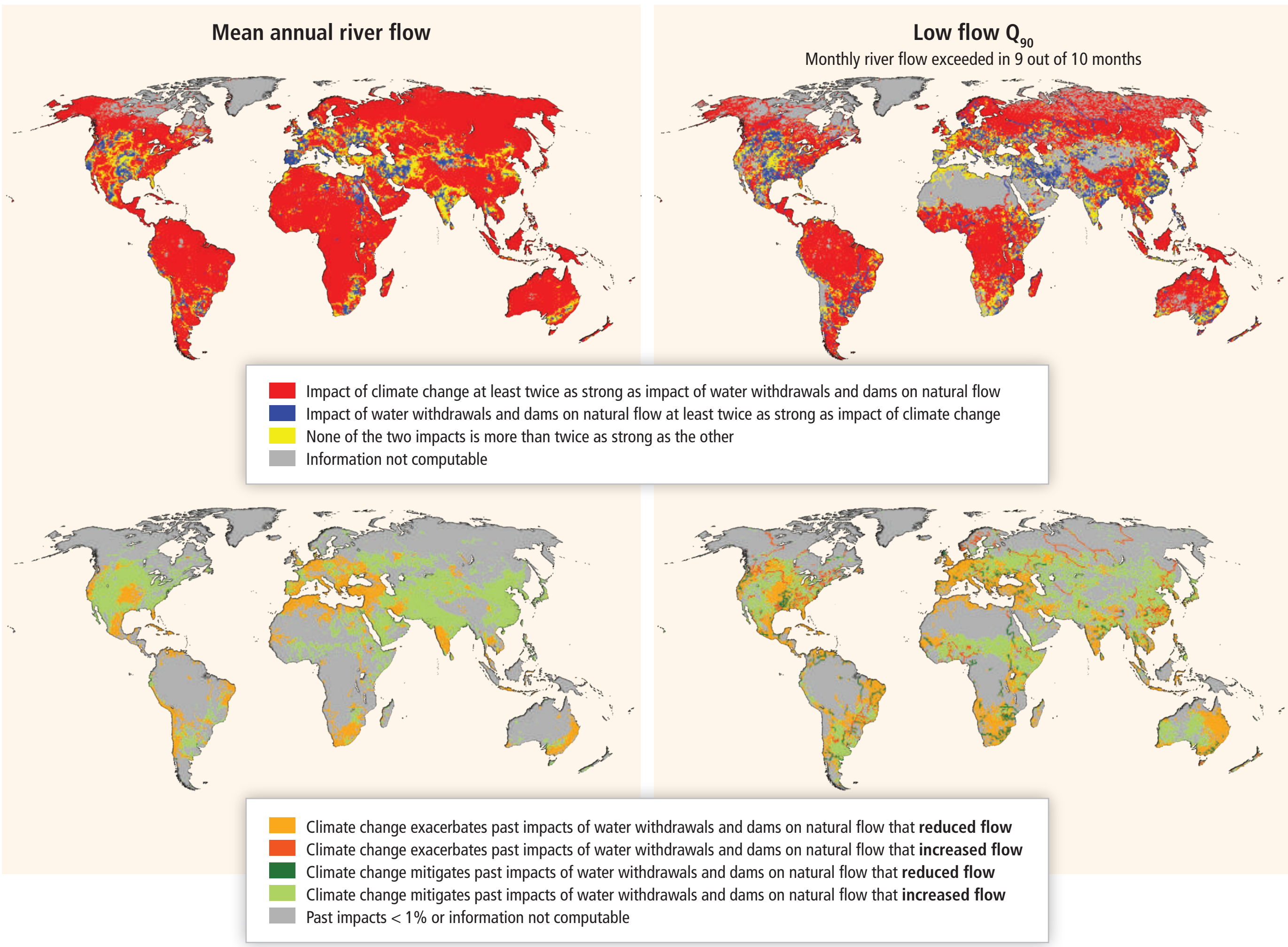

Figure RF-1 | Impact of climate change relative to the impact of water withdrawals and dams on natural flows for two ecologically relevant river flow characteristics (mean annual river flow and monthly low flow Q_{90}), computed by a global water model (Döll and Zhang, 2010). Impact of climate change is the percent change of flow between 1961–1990 and 2041–2070 according to the emissions scenario A2 as implemented by the global climate model Met Office Hadley Centre Coupled Model, version 3 (HadCM3). Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002. Please note that the figure does not reflect spatial differences in the magnitude of change.

Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases (Burkett et al., 2005; Vuille et al., 2008; Jacobsen et al., 2012). In the first phase, when river discharge is increased as a result of intensified melting, the overall diversity and abundance of species may increase. However, changes in water temperature and stream flow may have negative impacts on narrow range endemics (Jacobsen et al., 2012). In the second phase, when snowfields melt early and glaciers have shrunken to the point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).

River discharge also influences the response of river temperatures to increases of air temperature. Globally averaged, air temperature increases of 2°C, 4°C, and 6°C are estimated to lead to increases of annual mean river temperatures of 1.3°C, 2.6°C, and 3.8°C, respectively (van Vliet et al., 2011). Discharge decreases of 20% and 40% are computed to result in additional increases of river water temperature of 0.3° C and 0.8°C on average (van Vliet et al., 2011). Therefore, where rivers will experience drought more frequently in the future, freshwater-dependent biota will suffer not only directly by changed flow conditions but also by drought-induced river temperature increases, as well as by related decreased oxygen and increased pollutant concentrations.

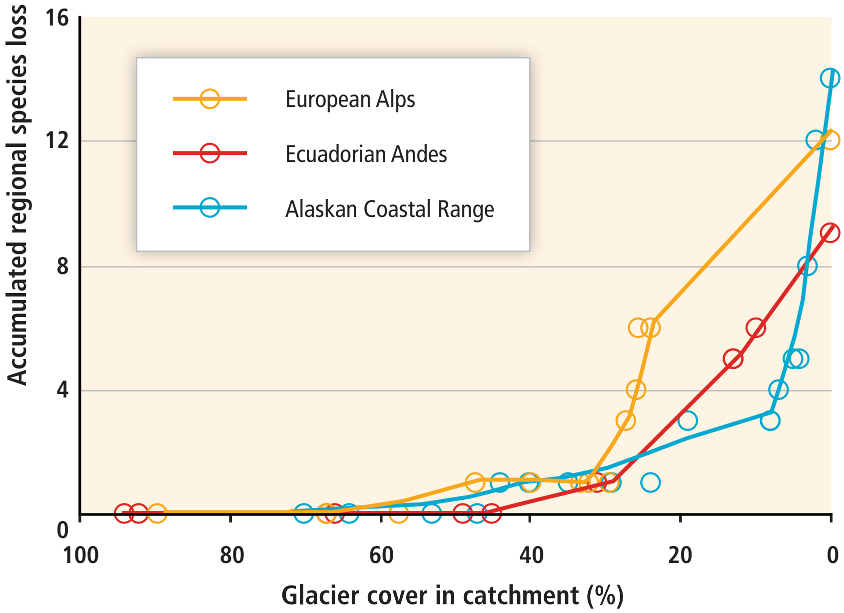

Figure RF-2 | Accumulated loss of regional species richness (gamma diversity) of macroinvertebrates as a function of glacial cover in catchment. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%, and 9 to 14 species are predicted to be lost with the complete disappearance of glaciers in each region, corresponding to 11, 16, and 38% of the total species richness in the three study regions in Ecuador, Europe, and Alaska. Data are derived from multiple river sites from the Ecuadorian Andes and Swiss and Italian Alps, and a temporal study of a river in the Coastal Range Mountains of southeast Alaska over nearly three decades of glacial shrinkage. Each data point represents a river site (Europe or Ecuador) or date (Alaska), and lines are Lowess fits. (Adapted by permission from Jacobsen et al., 2012.)

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TC

Building Long-Term Resilience from Tropical Cyclone Disasters

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Tropical cyclones (also referred to as hurricanes and typhoons in some regions) cause powerful winds, torrential rains, high waves, and storm surge, all of which can have major impacts on society and ecosystems. Bangladesh and India suffer 86% of mortality from tropical cyclones (Murray et al., 2012), which occurs mainly during the rarest and most severe storm categories (i.e., Categories 3, 4, and 5 on the Saffir–Simpson scale).

About 90 tropical cyclones occur globally each year (Seneviratne et al., 2012) although interannual variability is large. Changes in observing techniques, particularly after the introduction of satellites in the late 1970s, confounds the assessment of trends in tropical cyclone frequencies and intensities, which leads to *low confidence* that any observed long-term (i.e., 40 years or more) increases in tropical cyclone activity are robust, after accounting for past changes in observing capability (Seneviratne et al., 2012; Chapter 2). There is also *low confidence* in the detection and attribution of century scale trends in tropical cyclones. Future changes to tropical cyclones arising from climate change are *likely* to vary by region. This is because there is *medium confidence* that for certain regions, shorter-term forcing by natural and anthropogenic aerosols has had a measurable effect on tropical cyclones. Tropical cyclone frequency is *likely* to decrease or remain unchanged over the 21st century, while intensity (i.e., maximum wind speed and rainfall rates) is *likely* to increase (WGI AR5 Section 14.6). Regionally specific projections have *lower confidence* (see WGI AR5 Box 14.2).

Longer-term impacts from tropical cyclones include salinization of coastal soils and water supplies and subsequent food and water security issues from the associated storm surge and waves (Terry and Chui, 2012). However, preparation for extreme tropical cyclone events through improved governance and development to reduce their impacts provides an avenue for building resilience to longer-term changes associated with climate change.

Asian deltas are particularly vulnerable to tropical cyclones owing to their large population density in expanding urban areas (Nicholls et al., 2007). Extreme cyclones in Asia since 1970 caused more than 0.5 million fatalities (Murray et al., 2012), for example, cyclones Bhola in 1970, Gorky in 1991, Thelma in 1998, Gujarat in 1998, Orissa in 1999, Sidr in 2007, and Nargis in 2008. Tropical cyclone Nargis hit Myanmar on May 2, 2008 and caused more than 138,000 fatalities. Several-meter high storm surges widely flooded densely populated coastal areas of the Irrawaddy Delta and surrounding areas (Revenga et al., 2003; Brakenridge et al., 2013). The flooded areas were captured by a NASA Moderate Resolution Imaging Spectrometer (MODIS) image on May 5, 2008 (see Figure TC-1).

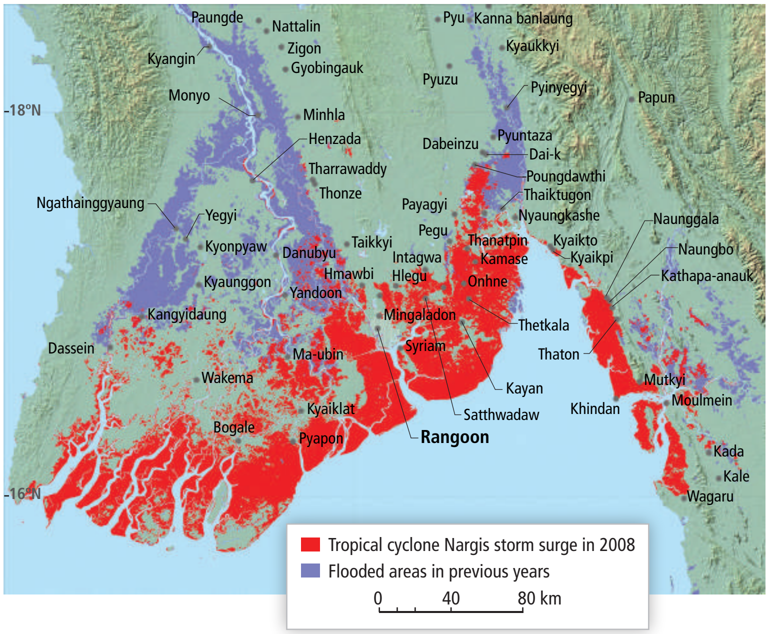

Figure TC-1 | The intersection of inland and storm surge flooding. Red shows May 5, 2008 Moderate Resolution Imaging Spectrometer (MODIS) mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The purple areas to the north were flooded by the river in prior years. (Source: Brakenridge et al., 2013.)

Murray et al. (2012) compared the response to cyclone Sidr in Bangladesh in 2007 and Nargis in Myanmar in 2008 and demonstrated how disaster risk reduction methods could be successfully applied to climate change adaptation. Sidr, despite being of similar strength to Nargis, caused far fewer fatalities (3400 compared to more than 138,000) and this was attributed to advancement in preparedness and response in Bangladesh through experience in previous cyclones such as Bhola and Gorky. The responses included the construction of multistoried cyclone shelters, improvement of forecasting and warning capacity, establishing a coastal volunteer network, and coastal reforestation of mangroves. Disaster risk management strategies for tropical cyclones in coastal areas create protective measures, anticipate and plan for extreme events, and increase the resilience of potentially exposed communities. The integration of activities relating to education, training, and awareness-raising into relevant ongoing processes and practices is important for the long-term success of disaster risk reduction and management (Murray et al., 2012). However, Birkmann and Teichman (2010) caution that while the combination of risk reduction and climate change adaptation strategies may be desirable, different spatial and temporal scales, norm systems, and knowledge types and sources between the two goals can confound their effective combination.

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UP

Uncertain Trends in Major Upwelling Ecosystems

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Upwelling is the vertical transport of cold, dense, nutrient-rich, relatively low-pH and often oxygen-poor waters to the euphotic zone where light is abundant. These conditions trigger high levels of primary production and a high biomass of benthic and pelagic organisms. The driving forces of upwelling include wind stress and the interaction of ocean currents with bottom topography. Upwelling intensity also depends on water column stratification. The major upwelling systems of the planet, the Equatorial Upwelling System (EUS; Section 30.5.2, Figure 30.1A) and the Eastern Boundary Upwelling Ecosystems (EBUE; Section 30.5.5, Figure 30.1A), represent only 10% of the ocean surface but contribute nearly 25% to global fish production (Figure 30.1B, Table SM30.1).

Marine ecosystems associated with upwelling systems can be influenced by a range of "bottom-up" trophic mechanisms, with upwelling, transport, and chlorophyll concentrations showing strong seasonal and interannual couplings and variability. These, in turn, influence trophic transfer up the food chain, affecting zooplankton, foraging fish, seabirds, and marine mammals.

There is considerable speculation as to how upwelling systems might change in a warming and acidifying ocean. Globally, the heat gain of the surface ocean has increased stratification by 4% (WGI Sections 3.2, 3.3, 3.8), which means that more wind energy is needed to bring deep waters to the surface. It is as yet unclear to what extent wind stress can offset the increased stratification, owing to the uncertainty in wind speed trends (WGI Section 3.4.4). In the tropics, observations of reductions in trade winds over several decades contrast more recent evidence indicating their strengthening since the late 1990s (WGI Section 3.4.4). Observations and modeling efforts in fact show diverging trends in coastal upwelling at the eastern boundaries of the Pacific and the Atlantic. Bakun (1990) proposed that the difference in rates of heat gain between land and ocean causes an increase in the pressure gradient, which results in increased alongshore winds and leads to intensified offshore transport of surface water through Ekman pumping and the upwelling of nutrient-rich, cold waters (Figure CC-UP). Some regional records support this hypothesis; others do not. There is considerable variability in warming and cooling trends over the past decades both within and among systems, making it difficult to predict changes in the intensity of all Eastern EBUEs (Section 30.5.5).

Understanding whether upwelling and climate change will impact resident biota in an additive, synergistic, or antagonistic manner is important for projections of how ecological goods and services provided for human society will change. Even though upwellings may prove more resilient to climate change than other ocean ecosystems because of their ability to function under extremely variable conditions (Capone and Hutchins, 2013), consequences of their shifts are highly relevant because these systems provide a significant portion of global primary productivity and fishery catch (Figure 30.1 A, B; Table SM30.1). Increased upwelling would enhance fisheries yields. However, the export of organic material from surface to deeper layers of the ocean may increase and stimulate its decomposition by microbial activity, thereby enhancing oxygen depletion and CO_2 enrichment in deeper water layers. Once this water returns to the surface through upwelling, benthic and pelagic coastal communities will be exposed to acidified and deoxygenated water which may combine with anthropogenic impact to negatively affect marine biota and ecosystem structure of the upper ocean (*high confidence*; Sections 6.3.2, 6.3.3, 30.3.2.2, 30.3.2.3). Extreme hypoxia may result in abnormal mortalities of fishes and invertebrates (Keller et al., 2010), reduce fisheries' catch potential, and impact aquaculture in coastal areas (Barton et al., 2012; see also Sections 5.4.3.3, 6.3.3, 6.4.1, 30.5.1.1.2, 30.5.5.1.3). Shifts in upwelling also coincide with an apparent increase in the frequency of submarine eruptions of methane and hydrogen sulfide gas, caused by enhanced formation and sinking of phytoplankton biomass to the hypoxic or anoxic sea floor. This combination of factors has been implicated in the extensive mortality of coastal fishes and invertebrates (Bakun and Weeks, 2004; Bakun et al., 2010), resulting in significant reductions in fishing productivity, such as Cape hake (*Merluccius capensis*), Namibia's most valuable fishery (Hamukuaya et al., 1998).

Reduced upwelling would also reduce the productivity of important pelagic fisheries, such as for sardines, anchovies and mackerel, with major consequences for the economies of several countries (Section 6.4.1, Chapter 7, Figure 30.1A, B, Table S30.1). However, under projected scenarios of reduced upward supply of nutrients due to stratification of the open ocean, upwelling of both nutrients and trace elements may become increasingly important to maintaining upper ocean nutrient and trace metal inventories. It has been suggested that upwelling areas may also increase nutrient content and productivity under enhanced stratification, and that upwelled and partially denitrified waters containing excess phosphate may select for N_2-fixing microorganisms (Deutsch et al., 2007; Deutsch and Weber, 2012), but field observations of N_2 fixation in these regions have not supported these predictions (Fernandez et al., 2011; Franz et al., 2012). The role of this process in global primary production thus needs to be validated (*low confidence*).

The central question therefore is whether or not upwelling will intensify, and if so, whether the effects of intensified upwelling on O_2 and CO_2 inventories will outweigh its benefits for primary production and associated fisheries and aquaculture (*low confidence*). In any case increasing atmospheric CO_2 concentrations will equilibrate with upwelling waters that may cause them to become more corrosive, depending on pCO_2 of the upwelled water, and potentially increasingly impact the biota of EBUEs.

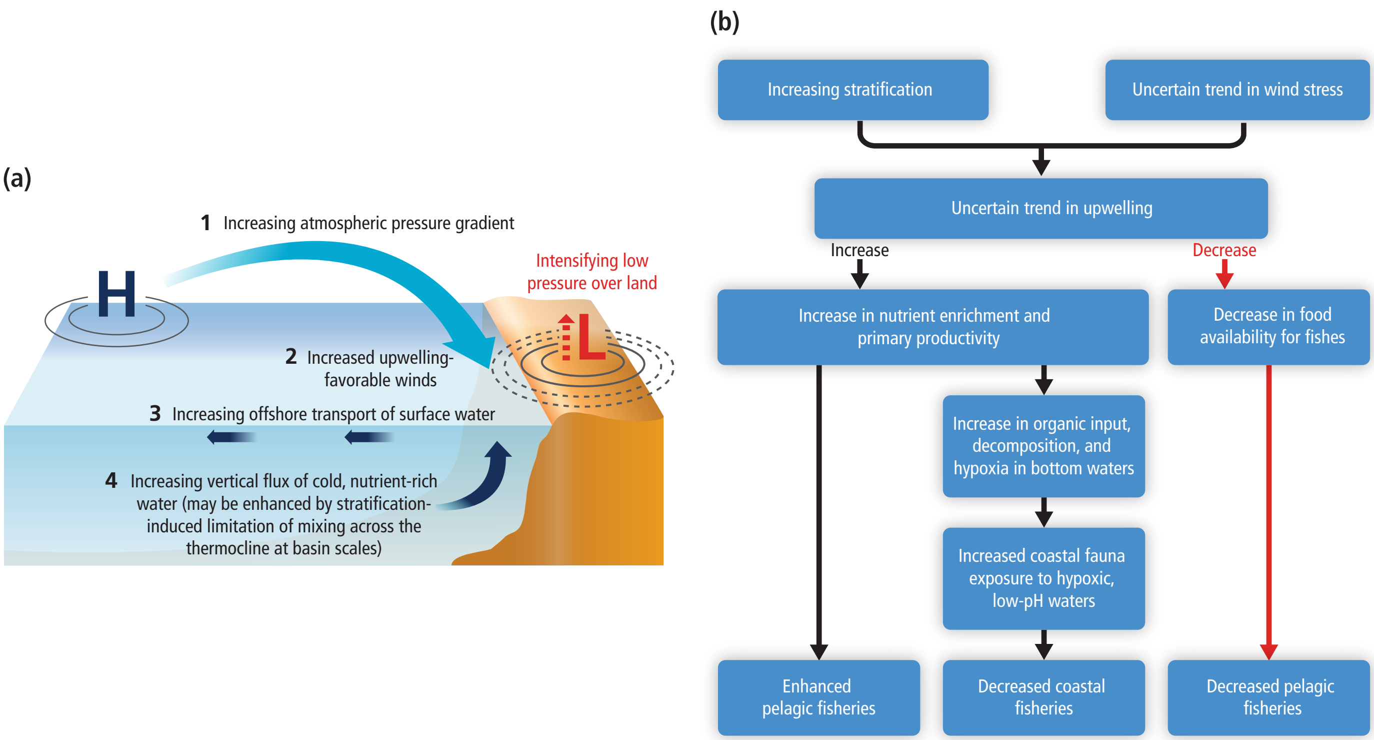

Figure UP-1 | (a) Hypothetic mechanism of increasing coastal wind–driven upwelling at Equatorial and Eastern Boundary upwelling systems (EUS, EBUE, Figure 30-1), where differential warming rates between land and ocean results in increased land–ocean (1) pressure gradients that produce (2) stronger alongshore winds and (3) offshore movement of surface water through Ekman transport, and (4) increased upwelling of deep cold nutrient rich waters to replace it. (b) Potential consequences of climate change in upwelling systems. Increasing stratification and uncertainty in wind stress trends result in uncertain trends in upwelling. Increasing upwelling may result in higher input of nutrients to the euphotic zone, and increased primary production, which in turn may enhance pelagic fisheries, but also decrease coastal fisheries due to an increased exposure of coastal fauna to hypoxic, low pH waters. Decreased upwelling may result in lower primary production in these systems with direct impacts on pelagic fisheries productivity.

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UR

Urban–Rural Interactions – Context for Climate Change Vulnerability, Impacts, and Adaptation

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Rural areas and urban areas have always been interconnected and interdependent, but recent decades have seen new forms of these interconnections: a tendency for rural–urban boundaries to become less well defined, and new types of land use and economic activity on those boundaries. These conditions have important implications for understanding climate change impacts, vulnerabilities, and opportunities for adaptation. This box examines three critical implications of these interactions:

1) Climate extremes in rural areas resulting in urban impacts— teleconnections of resources and migration streams mean that climate extremes in non-urban locations with associated shifts in water supply, rural agricultural potential, and the habitability of rural areas will have downstream impacts in cities.
2) Events specific to the rural–urban interface— given the highly integrated nature of rural–urban interface areas and overarching demand to accommodate both rural and urban demands in these settings, there is a set of impacts, vulnerabilities, and opportunities for adaptation specific to these locations. These impacts include loss of local agricultural production, economic marginalization resulting from being neither rural or urban, and stress on human health.
3) Integrated infrastructure and service disruption—as urban demands often take preference, interdependent rural and urban resource systems place nearby rural areas at risk, because during conditions of climate stress, rural areas more often suffer resource shortages or other disruptions to sustain resources to cities. For example, under conditions of resource stress associated with climate risk (e.g., droughts) urban areas are at an advantage because of political, social, and economic requirements to maintain service supply to cities to the detriment of relatively marginal rural sites and settlements.

Urban areas historically have been dependent on the lands just beyond their boundaries for most of their critical resources including water, food, and energy. Although in many contexts, the connections between urban settlements and surrounding rural areas are still present, long distance, teleconnected, large-scale supply chains have been developed particularly with respect to energy resources and food supply (Güneralp et al., 2013). Extreme event disruptions in distant resource areas or to the supply chain and relevant infrastructure can negatively impact the urban areas dependent on these materials (Wilbanks et al., 2012). During the summer of 2012, for instance, an extended drought period in the central United States led to significantly reduced river levels on the Mississippi River that led to interruptions of barge traffic and delay of commodity flows to cities throughout the country. Urban water supply is also vulnerable to droughts in predominantly rural areas. In the case of Bulawayo, Zimbabwe, periodic urban water shortages over the last few decades have been triggered by rural droughts (Mkandla et al., 2005).

A further teleconnection between rural and urban areas is rural–urban migration. There have been cases where migration and urbanization patterns have been to attributed to climate change or its proxies such as in parts of Africa (Morton, 1989; Barrios et al., 2006). However, as recognized by Black et al. (2011), life in rural areas across the world typically involves complex patterns of rural–urban and rural–rural migration, subject to economic, political, social, and demographic drivers, patterns that are modified or exacerbated by climate events and trends rather than solely caused by them.

Globally, an increased blending of urban and rural qualities has occurred. Simon et al. (2006, p. 4) assert that the simple dichotomy between "rural" and "urban" has "long ceased to have much meaning in practice or for policy-making purposes in many parts of the global South." One approach to reconciling this is through the increasing application of the concept of "peri-urban areas" (Simon et al., 2006; Simon, 2008). These areas can be seen as rural locations that have "become more urban in character" (Webster, 2002, p. 5); as sites where households pursue a wider range of income-generating activities while still residing in what appear to be "largely rural landscapes" (Learner and Eakin, 2010, p. 1); or as locations in which rural and urban land uses coexist, whether in contiguous or fragmented units (Bowyer-Bower, 2006). The inhabitants of "core" urban areas within cities have also increasingly turned to agriculture, with production of staple foods, higher value crops and livestock (Bryld, 2003; Devendra et al., 2005; Lerner and Eakin, 2010; Lerner et al., 2013). Bryld (2003) sees this as driven by rural–urban migration and by structural adjustment (e.g., withdrawal of food price controls and food subsidies). Lerner and Eakin (2011; also Lerner et al., 2013) explored reasons why people produce food in urban environments, despite high opportunity costs of land and labor: buffering of risk from insecure urban labor markets; response to consumer demand; and the meeting of cultural needs.

Livelihoods and areas on the rural–urban interface suffer highly specific forms of vulnerability to disasters, including climate-related disasters. These may be summarized as specifically combining urban vulnerabilities of population concentration, dependence on infrastructure, and social diversity limiting social support with rural traits of distance, isolation, and invisibility to policymakers (Pelling and Mustafa, 2010). Increased connectivity can also encourage land expropriation to enable commercial land development (Pelling and Mustafa, 2010). Vulnerability may arise from the coexistence of rural and urban perspectives, which may give rise to conflicts between different social/interest groups and economic activities (Masuda and Garvin, 2008; Solona-Solona 2010; Darly and Torre, 2013).

Additional vulnerability of peri-urban areas is on account of the re-constituted institutional arrangements and their structural constraints (Iaquinta and Drescher, 2000). Rapid declines in traditional informal institutions and forms of collective action, and their imperfect replacement with formal state and market institutions, may also increase vulnerability (Pelling and Mustafa, 2010).

Peri-urban areas and livelihoods have low visibility to policymakers at both local and national levels, and may suffer from a lack of necessary services and inappropriate and uncoordinated policies. In Tanzania and Malawi, national policies of agricultural extension to farmer groups, for example, do not reach peri-urban farmers (Liwenga et al., 2012). In peri-urban areas around Mexico City (Eakin et al., 2013), management of the substantial risk of flooding is led *de facto* by agricultural and water agencies, in the absence of capacity within peri-urban municipalities and despite clear evidence that urban encroachment is a key driver of flood risk. In developed country contexts, suburban–exurban fringe areas often are overlooked in the policy arena that traditionally focuses on rural development and agricultural production, or urban growth and services (Hanlon et al., 2010). The environmental function of urban agriculture, in particular, in protection against flooding, will increase in the context of climate change (Aubry et al., 2012).

However, peri-urban areas and mixed livelihoods more generally on rural–urban interfaces, also exhibit specific factors that increase their resilience to climate shocks (Pelling and Mustafa, 2010). Increased transport connectivity in peri-urban areas can reduce disaster risk by providing a greater diversity of livelihood options and improving access to education. The expansion of local labor markets and wage labor in these areas can strengthen adaptive capacity through providing new livelihood opportunities (Pelling and Mustafa, 2010). Maintaining mixed portfolios of agricultural and non-agricultural livelihoods also spreads risk (Lerner et al., 2013).

In high-income countries, practices attempting to enhance the ecosystem services and localized agriculture more typically associated with lower density areas have been encouraged. In many situations these practices are focused increasingly on climate adaptation and mitigating the impacts of climate extremes such as those associated with heating and the urban heat island effect, or wetland restoration efforts to limit the impact of storm surge wave action (Verburg et al., 2012).

The dramatic growth of urban areas also implies that rural areas and communities are increasingly politically and economically marginalized within national contexts, resulting in potential infrastructure and service disruptions for such sites. Existing rural–urban conflicts for the management of natural resources (Castro and Nielsen, 2003) such as water (Celio et al., 2011) or land use conversion in rural areas, for example, wind farms in rural Catalonia (Zografos and Martínez-Alier, 2009); industrial coastal areas in Sweden (Stepanova and Bruckmeier, 2013); or conversion of rice land into industrial, residential, and recreational uses in the Philippines (Kelly, 1998) have been documented, and it is expected that stress from climate change impacts on land and natural resources will exacerbate these tensions. For instance, climate-induced reductions in water availability may be more of a concern than population growth or increased per capita use for securing continued supplies of water to large cities (Jenerette and Larsen, 2006), which requires an innovative approach to address such conflicts (Pearson et al., 2010).

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VW

Active Role of Vegetation in Altering Water Flows under Climate Change

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Climate, vegetation, and carbon and water cycles are intimately coupled, in particular via the simultaneous transpiration and CO_2 uptake through plant stomata in the process of photosynthesis. Hence, water flows such as runoff and evapotranspiration are affected not only directly by anthropogenic climate change as such (i.e., by changes in climate variables such as temperature and precipitation), but also indirectly by plant responses to increased atmospheric CO_2 concentrations. In addition, effects of climate change (e.g., higher temperature or altered precipitation) on vegetation structure, biomass production, and plant distribution have an indirect influence on water flows. Rising CO_2 concentration affects vegetation and associated water flows in two contrasting ways, as suggested by ample evidence from Free Air CO_2 Enrichment (FACE), laboratory and modeling experiments (e.g., Leakey et al., 2009; Reddy et al., 2010; de Boer et al., 2011). On the one hand, a *physiological* effect leads to reduced opening of stomatal apertures, which is associated with lower water flow through the stomata, that is, lower leaf-level transpiration. On the other hand, a *structural* effect ("fertilization effect") stimulates photosynthesis and biomass production of C_3 plants including all tree species, which eventually leads to higher transpiration at regional scales. A key question is to what extent the climate- and CO_2-induced changes in vegetation and transpiration translate into changes in regional and global runoff.

The physiological effect of CO_2 is associated with an increased intrinsic water use efficiency (WUE) of plants, which means that less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas et al., 2011) verify this finding, suggesting an increase in WUE of mature trees by 20.5% between the early 1960s and the early 2000s. Increases since pre-industrial times have also been found for several forest sites (Andreu-Hayles et al., 2011; Gagen et al., 2011; Loader et al., 2011; Nock et al., 2011) and in a temperate semi-natural grassland (Koehler et al., 2010), although in one boreal tree species WUE ceased to increase after 1970 (Gagen et al., 2011). Analysis of long-term whole-ecosystem carbon and water flux measurements from 21 sites in North American temperate and boreal forests corroborates a notable increase in WUE over the two past decades (Keenan et al., 2013). An increase in global WUE over the past century is supported by ecosystem model results (Ito and Inatomi, 2012).

A key influence on the significance of increased WUE for large-scale transpiration is whether vegetation structure and production has remained approximately constant (as assumed in the global modeling study by Gedney et al., 2006) or has increased in some regions due to the structural CO_2 effect (as assumed in models by Piao et al., 2007; Gerten et al., 2008). While field-based results vary considerably among sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and CO_2 change (Andreu-Hayles et al., 2011; Peñuelas et al., 2011). However, basal area measurements at more than 150 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis et al., 2009). This is also confirmed for 55 temperate forest plots, with a suspected contribution of CO_2 effects (McMahon et al., 2010). Satellite observations analyzed in Donohue et al. (2013) suggest that an increase in vegetation cover by 11% in warm drylands (1982–2010 period) is attributable to CO_2 fertilization. Owing to the interplay of physiological and structural effects, the net impact of CO_2 increase on global-scale transpiration and runoff remains rather poorly constrained. This is also true because nutrient limitation, often omitted in modeling studies, can suppress the CO_2 fertilization effect (see Rosenthal and Tomeo, 2013).

Therefore, there are conflicting views on whether the direct CO_2 effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney et al. (2006) that suggested that the physiological CO_2 effect (lower transpiration) contributed to a supposed increase in global runoff seen in reconstructions by Labat et al. (2004). However, a more recent analysis based on a more complete data set (Dai et al., 2009) suggested that river basins with decreasing runoff outnumber basins with increasing runoff, such that a small decline in global runoff is *likely* for the period 1948–2004. Hence, detection of vegetation contributions to changes in water flows critically depends on the availability and quality of hydrometeorological observations (Haddeland et al., 2011; Lorenz and Kunstmann, 2012). Overall, the evidence since AR4 suggests that climatic variations and trends have been the main driver of global runoff change in the past decades; both CO_2 increase and land use change have contributed less (Piao et al., 2007; Gerten et al., 2008; Alkama et al., 2011; Sterling et al., 2013). Oliveira et al. (2011) furthermore pointed to the importance of changes in incident solar radiation and the mediating role of vegetation; according to their global simulations, a higher diffuse radiation fraction during 1960–1990 may have increased evapotranspiration in the tropics by 3% due to higher photosynthesis from shaded leaves.

It is uncertain how vegetation responses to future increases in CO_2 and to climate change will modulate the impacts of climate change on freshwater flows. Twenty-first century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when the physiological CO_2 effect is included in addition to climate change effects (Betts et al., 2007; Murray et al., 2012). This could somewhat ease the increase in water scarcity anticipated in response to future climate change and population growth (Gerten et al., 2011; Wiltshire et al., 2013). In absolute terms, the isolated effect of CO_2 has been modeled to increase future global runoff by 4 to 5% (Gerten et al., 2008) up to 13% (Nugent and Matthews, 2012) compared to the present, depending on the assumed CO_2 trajectory and whether feedbacks of changes in vegetation structure and distribution to the atmosphere are accounted for (they were in Nugent and Matthews, 2012). In a global model intercomparison study (Davie et al., 2013), two out of four models projected stronger increases and, respectively, weaker decreases in runoff when considering CO_2 effects compared to simulations with constant CO_2 concentration (consistent with the above findings, though magnitudes differed between the models), but two other models showed the reverse. Thus, the choice of models and the way they represent the coupling between CO_2, stomatal closure, and plant growth is a source of uncertainty, as also suggested by Cao et al. (2009). Lower transpiration due to rising CO_2 concentration may also affect future regional climate change itself (Boucher et al., 2009) and enhance the contrast between land and ocean surface warming (Joshi et al., 2008). Overall, although physiological and structural effects will influence water flows in many regions, precipitation and temperature effects are *likely* to remain the prime influence on global runoff (Alkama et al., 2010).

An application of a soil–vegetation–atmosphere–transfer model indicates complex responses of groundwater recharge to vegetation-mediated changes in climate, with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum et al., 2010). Another study found that even if precipitation slightly decreased, groundwater recharge might increase as a net effect of vegetation responses to climate change and CO_2 rise, that is, increasing WUE and either increasing or decreasing leaf area (Crosbie et al., 2010). Depending on the type of grass in Australia, the same change in climate is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green et al., 2007). For a site in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma et al., 2010).

Using a large ensemble of climate change projections, Konzmann et al. (2013) put hydrological changes into an agricultural perspective and suggested that the net result of physiological and structural CO_2 effects on crop irrigation requirements would be a global reduction (Figure VW-1). Thus, adverse climate change impacts on irrigation requirements and crop yields might be partly buffered as WUE and crop production improve (Fader et al., 2010). However, substantial CO_2-driven improvements will be realized only if proper management abates limitation of plant growth by nutrient availability or other factors.

Changes in vegetation coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg et al., 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving complex feedbacks with the atmosphere such as in the Amazon region (Port et al., 2012; Saatchi et al., 2013). One model in the study by Davie et al. (2013) showed regionally diverse climate change effects on vegetation distribution and structure, which had a much weaker effect on global runoff than the structural and physiological CO_2 effects. As water, carbon, and vegetation dynamics evolve synchronously and interactively under climate change (Heyder et al., 2011; Gerten et al., 2013), it remains a challenge to disentangle the individual effects of climate, CO_2, and land cover change on the water cycle.

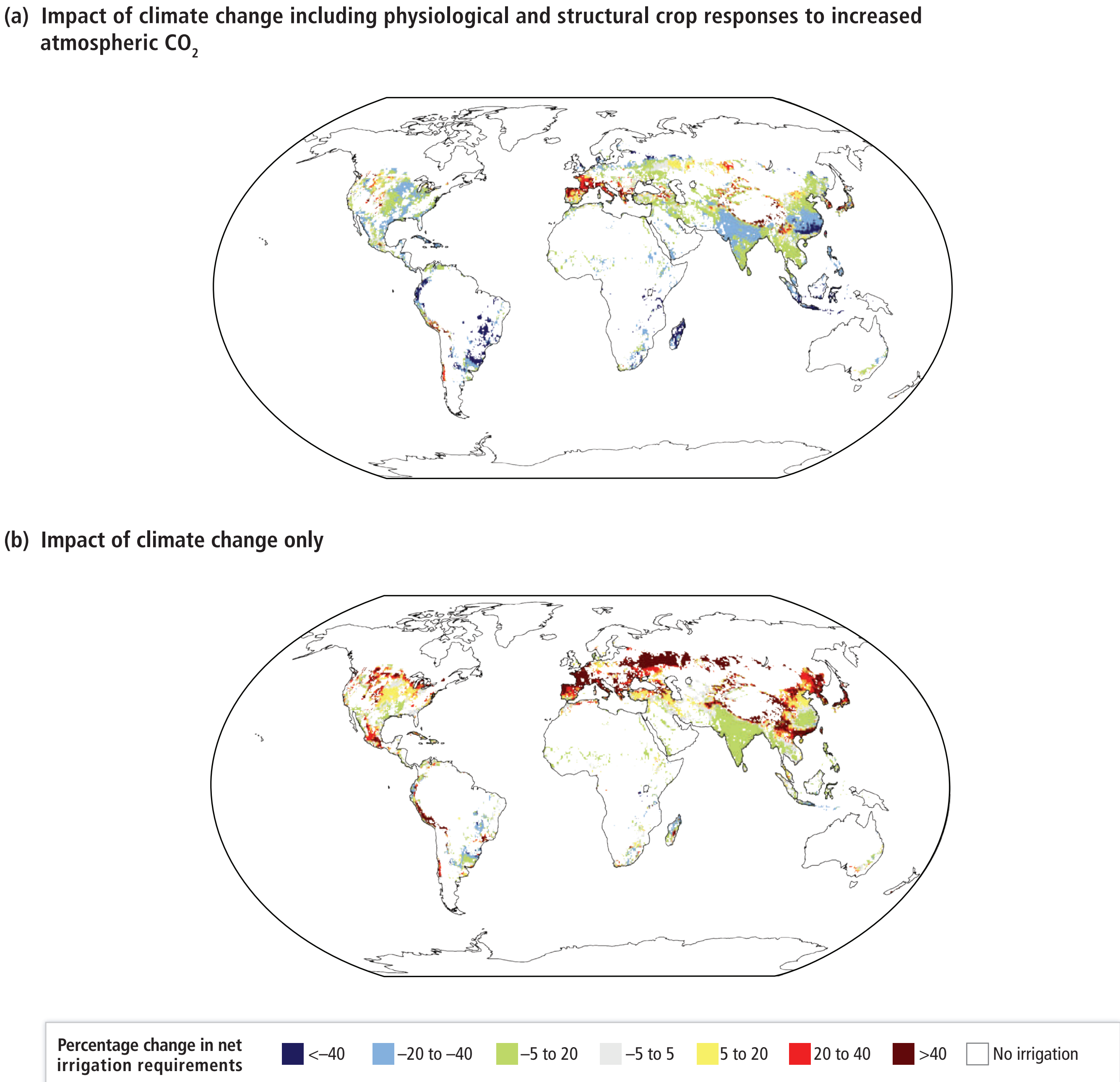

Figure VW-1 | Percentage change in net irrigation requirements of 11 major crops from 1971–2000 to 2070–2099 on areas currently equipped for irrigation, assuming current management practices. (a) Impact of climate change including physiological and structural crop responses to increased atmospheric CO_2 concentration (co-limitation by nutrients not considered). (b) Impact of climate change only. Shown is the median change derived from climate change projections by 19 General Circulation Models (GCMs; based on the Special Report on Emission Scenarios (SRES) A2 emissions scenario) used to force a vegetation and hydrology model. (Modified after Konzmann et al., 2013.)

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The Water–Energy–Food/Feed/Fiber Nexus as Linked to Climate Change

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Water, energy, and food/feed/fiber are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure CC-WE-1. The depth and intensity of those linkages vary enormously among countries, regions, and production systems. Energy technologies (e.g., biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops and forages) may require significant amounts of water (Sections 3.7.2, 7.3.2, 10.2,10.3.4, 22.3.3, 25.7.2; Allan, 2003; King and Weber, 2008; McMahon and Price, 2011; Macknick et al., 2012a). In irrigated agriculture, climate, irrigating procedure, crop choice, and yields determine water requirements per unit of produced crop. In areas where water (and wastewater) must be pumped and/or treated, energy must be provided (Metcalf & Eddy, Inc. et al., 2007; Khan and Hanjra, 2009; EPA, 2010; Gerten et al., 2011). While food production, refrigeration, transport, and processing require large amounts of energy (Pelletier et al., 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (*robust evidence, high agreement*; Section 7.3.2, Box 25-10; Diffenbaugh et al., 2012; Skaggs et al., 2012). Food and crop wastes, and wastewater, may be used as sources of energy, saving not only the consumption of conventional nonrenewable fuels used in their traditional processes, but also the consumption of the water and energy employed for processing or treatment and disposal (Schievano et al., 2009; Oh et al., 2010; Olson, 2012). Examples of this can be found in several countries across all income ranges. For example, sugar cane byproducts are increasingly used to produce electricity or for cogeneration (McKendry, 2002; Kim and Dale, 2004) for economic benefits, and increasingly as an option for greenhouse gas mitigation.

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (*robust evidence, high agreement*; Sections 10.2.2, 10.3.4, 25.7.4; and van Vliet et al., 2012; Davies et al., 2013. Water for biofuels, for example, under the International Energy Agency (IEA) Alternative Policy Scenario, which has biofuels production increasing to 71 EJ in 2030, has been reported by Gerbens-Leenes et al. (2012) to drive global consumptive irrigation water use from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water is also required for mining (Section 25.7.3), processing, and residue disposal of fossil and nuclear fuels or their byproducts. Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country (Kenny et al., 2009; WEC, 2010). Future water requirements will depend on electricity demand growth, the portfolio of generation technologies and water management options employed (*medium evidence, high agreement*; WEC, 2010; Sattler et al.,

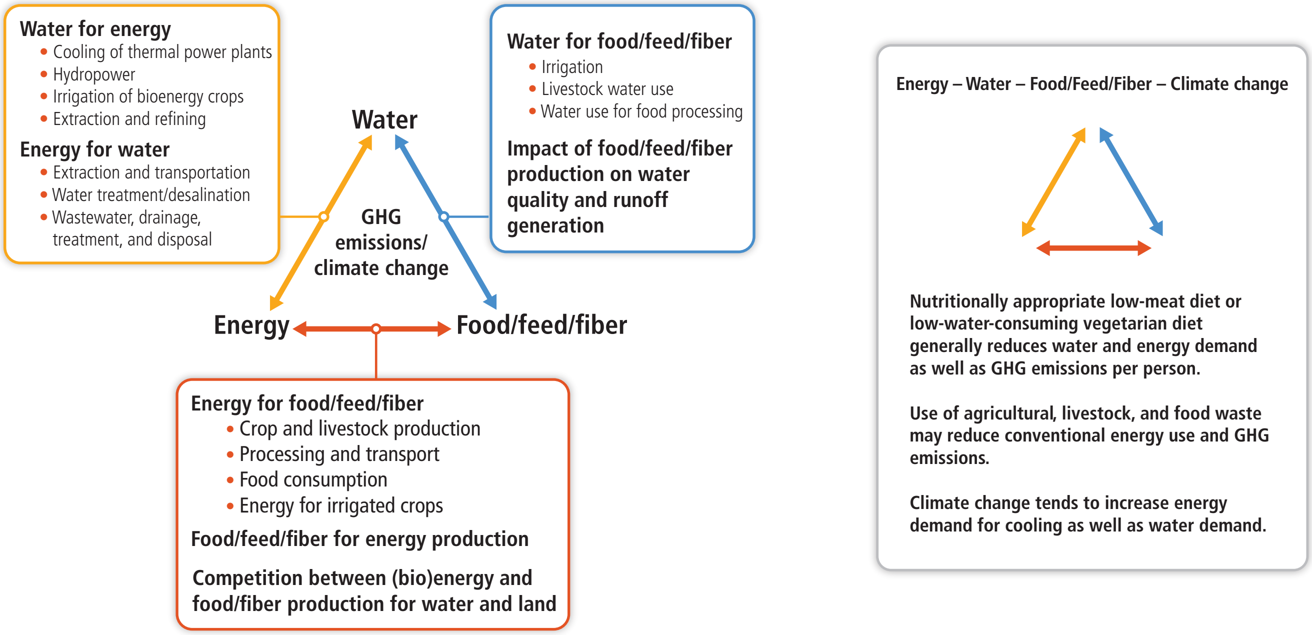

Figure WE-1 | The water–energy–food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, and energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.

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2012). Future water availability for energy production will change due to climate change (*robust evidence, high agreement*; Sections 3.4, 3.5.1, 3.5.2.2.

Water may require significant amounts of energy for lifting, transport, and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, for example, locally produced potable water from ground/surface water sources versus desalinated seawater (Box 25-2, Tables 25-6, 25-7; Macknick et al., 2012b; Plappally and Lienhard, 2012). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user; Döll et al., 2012) is generally more energy intensive than surface water. In India, for example, 19% of total electricity use in 2012 was for agricultural purposes (Central Statistics Office, 2013), with a large share for groundwater pumping. Pumping from greater depth increases energy demand significantly—electricity use (kWh m^{-3} of water) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard, 2012). The reuse of appropriate wastewater for irrigation (reclaiming both water and energy-intense nutrients) may increase agricultural yields, save energy, and prevent soil erosion (*medium confidence*; Smit and Nasr, 1992; Jiménez-Cisneros, 1996; Qadir et al., 2007; Raschid-Sally and Jayakody, 2008). More energy efficient treatment methods enable poor quality ("black") wastewater to be treated to quality levels suitable for discharge into water courses, avoiding additional freshwater and associated energy demands (Keraita et al., 2008). If properly treated to retain nutrients, such treated water may increase soil productivity, contributing to increased crop yields/food security in regions unable to afford high power bills or expensive fertilizer (*high confidence*; Oron, 1996; Lazarova and Bahri, 2005; Redwood and Huibers, 2008; Jiménez-Cisneros, 2009).

Linkages among water, energy, food/feed/fiber, and climate are also strongly related to land use and management (*robust evidence, high agreement*; Section 4.4.4, Box 25-10). Land degradation often reduces efficiency of water and energy use (e.g., resulting in higher fertilizer demand and surface runoff), and compromises food security (Sections 3.7.2, 4.4.4). On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat (see Box 25-10) but may reduce renewable water resources. Water abstraction for energy, food, or biofuel production or carbon sequestration can also compete with minimal environmental flows needed to maintain riverine habitats and wetlands, implying a potential conflict between economic and other valuations and uses of water (*medium evidence, high agreement*; Sections 25.4.3, 25.6.2, Box 25-10). Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water and climate (McCornick et al., 2008; Bazilian et al., 2011; Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy and water demand, bioproductivity, and other factors (see Figure CC-WE-1 and Wise et al., 2009), and has implications for security of supplies of energy, food, and water; adaptation and mitigation pathways; and air pollution reduction, as well as the implications for health and economic impacts as described throughout this Assessment Report.

The interconnectivity of food/fiber, water, land use, energy, and climate change, including the perhaps not yet well understood cross-sector impacts, are increasingly important in assessing the implications for adaptation/mitigation policy decisions. Fuel–food–land use–water–greenhouse gas (GHG) mitigation strategy interactions, particularly related to bioresources for food/feed, power, or fuel, suggest that combined assessment of water, land type, and use requirements, energy requirements, and potential uses and GHG impacts often epitomize the interlinkages. For example, mitigation scenarios described in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) indicate up to 300 EJ of biomass primary energy by 2050 under increasingly stringent mitigation scenarios. Such high levels of biomass production, in the absence of technology and process/management/operations change, would have significant implications for land use, water, and energy, as well as food production and pricing. Consideration of the interlinkages of energy, food/feed/fiber, water, land use, and climate change is increasingly recognized as critical to effective climate resilient pathway decision making (*medium evidence, high agreement*), although tools to support local- and regional-scale assessments and decision support remain very limited.

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Chapters 1-20

1 Point of Departure

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Frequently Asked Questions

1.1: On what information is the new assessment based, and how has that information changed since the last report, the IPCC Fourth Assessment Report in 2007? 174

1.2: How is the state of scientific understanding and uncertainty communicated in this assessment? 176

1.3: How has our understanding of the interface between human, natural, and climate systems expanded since the 2007 IPCC Assessment? 180

Executive Summary

The evolution of the IPCC assessments of impacts, adaptation, and vulnerability indicates an increasing emphasis on human beings, their role in managing resources and natural systems, and the societal impacts of climate change. The expanded focus on societal impacts and responses is evident in the composition of the IPCC author teams, the literature assessed, and the content of the IPCC assessment reports. Characteristics in the evolution of the Working Group II assessment reports are an increasing attention to (1) adaptation limits and transformation in social and natural systems; (2) synergies between multiple variables and factors that affect sustainable development; (3) risk management; and (4) institutional, social, cultural, and value-related issues. {1.1, 1.2}

The literature available for assessing climate change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, allowing for a more robust assessment that supports policymaking (*high confidence*). The diversity of the topics and regions covered by the literature has similarly expanded, as has the geographic distribution of authors contributing to the knowledge base for climate change assessments. Authorship of literature from developing countries has increased, although still representing a small fraction of the total. This unequal distribution of literature presents a challenge to the production of a comprehensive and balanced global assessment. {1.1.1, Figure 1-1}

Rapidly advancing climate science provides policy-relevant information that creates opportunities for decision making that can lead to climate-resilient development pathways (*robust evidence, medium agreement*). Climate change is just one of many stressors that influence resilience. The decisions that societies make within this opportunity space, also informed by observation, experience, and other factors, affect outcomes in human and natural systems. {1.1.1, 1.1.4, Figure 1-5}

Adaptation has emerged as a central area of climate change research, in country level planning, and in the implementation of climate change strategies (*high confidence*). The body of literature, including government and private sector reports, shows an increased focus on adaptation opportunities and the interrelations between adaptation, mitigation, and alternative sustainable pathways. The literature shows an emergence of studies on transformative processes that take advantage of synergies between adaptation planning, development strategies, social protection, and disaster risk reduction and management. {1.1.4}

As a core feature and innovation of IPCC assessment, major findings are presented with defined, calibrated language that communicates the strength of scientific understanding, including uncertainties and areas of disagreement. Each finding is supported by a traceable account of the evaluation of evidence and agreement. {1.1.2.2, Box 1-1}

Impacts assessed in this report are based on climate model projections using both the IPCC Special Report on Emission Scenarios (SRES) and the new Representative Concentration Pathway (RCP) scenarios. The RCPs span the range of SRES scenarios for long-lived greenhouse gases, but they have a narrower range in terms of emissions of ozone and aerosol precursors and related pollutants. The SRES scenarios were used in the Third Assessment Report (TAR) and the Fourth Assessment Report (AR4). With AR5, the RCP scenarios present both emissions and greenhouse gas concentration pathways, and corresponding Shared Socioeconomic Pathways (SSPs) have been developed. The four RCPs describe different levels of mitigation leading to 21st century radiative forcing levels of about 2.6, 4.5, 6.0, and 8.5 W m^{-2}), whereas the SRES scenarios are policy-independent. {1.1.3, 1.3.3, 19.6.3.1, Boxes 21-1, 21.5.4, 24.3.3; see also WGI AR5 Chapters 1, 8, 11, 12}

1

1.1. The Setting

This chapter describes the information basis for the Fifth Assessment Report (AR5) of IPCC Working Group II (WGII) and the rationale for its structure. As the starting point of WGII AR5, the chapter begins with an analysis of how the literature for the assessment has developed through time and proceeds with an overview of how the framing and content of the WGII reports have changed since the first IPCC report was published in 1990. The future climate scenarios used in AR5 are a marked change from those used in the Third (TAR, 2001) and Fourth (AR4, 2007) Assessment Reports; this shift is described here, along with the new AR5 guidance for communicating scientific uncertainty. The chapter provides a summary of the most relevant key findings from the IPCC *Special Report on Renewable Energy Sources and Climate Change Mitigation* (IPCC, 2011), the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, 2012), and the AR5 Working Group I (*The Physical Science Basis*) and AR5 Working Group III (*Mitigation of Climate Change*). Collectively these recent reports, new scenarios, and other advancements in climate change science set the stage for an assessment of impacts, adaptation, and vulnerability that could potentially overcome many of the limitations identified in the IPCC WGII AR4, particularly with respect to the human dimensions of climate change.

The critical review and synthesis of the scientific literature published since October 2006 (effective cutoff date for AR4) has required an expanded multidisciplinary approach that, in general, has focused more heavily on societal impacts and responses. This includes an assessment of impacts associated with coupled socio-ecological systems and the rapid emergence of research on adaptation and vulnerability.

WGII AR5 differs from the prior assessments primarily in the expanded outline and diversity of content that stems directly from the growth of the scientific basis for the assessment. WGII AR5 is published in two volumes (Part A: Global and Sectoral Aspects; Part B: Regional Aspects), permitting the presentation of more detailed regional analyses and an expanded coverage of the human dimensions such as adaptation. WGI AR5 was completed approximately 6 months in advance of WGII AR5, allowing the WGII authors more time to evaluate and include where possible the WGI findings; WGIII AR5 was developed almost in parallel with the WGII report.

The point of departure in the title alludes to the availability of new information concerning the interactions between climate change and other biophysical and societal stressors. Societal stressors include poverty and inequality, low levels of human development, and psychological, institutional, and cultural factors. Even in the presence of these multiple stressors, policy relevant information from scientific research, direct experience, and observation provides an opportunity space to choose and design climate-resilient development pathways (see Sections 1.1.4, 13.1.1, 14.2, 14.3; Figure 1-5).

1.1.1. Development of the Science Basis for the Assessment

The volume of literature available for assessing Climate Change Impacts, Adaptation, and Vulnerability (CCIAV) has grown significantly over the past 2 decades (Figure 1-1). A bibliometric analysis of reports produced with two bibliographic search tools (Scopus[1] and ISI Web of Science[2]) indicates that fewer than 1000 articles in journals, books, and conference proceedings were published in English on the topic of "climate change" between 1970 and 1990. By the end of 2012 the total number of such articles was reported as 102,573 (Scopus) and 62,155 (Web of Science). The current doubling rate of "climate change" publications remains short, less than 5 years: Scopus database lists 32,943 articles published between 1970 and 2005, and 76,130 published between 1970 and 2010. The number of publications per year on the topic of climate change impacts between 2005 and 2010 and on the topic of climate change adaptation between 2008 and 2010 has roughly doubled (Figure 1-1c). Thus, the total number of publications more than doubled from 2005 to 2010.

Since 1990 the geographic distribution of authors contributing to the climate change literature has expanded from Europe and North America to include a large fraction from Asia and Australasia. Literature from scientists affiliated with institutions in Africa and Central and South America, however, comprised approximately 5% of the total during 2001–2010 (Figure 1-1a). The proportion of literature focusing on individual countries within IPCC regions has also broadened over the past 3 decades, particularly for Asia (Figure 1-1b).[3] This brief chronicle neither differentiates across the various "subcategories" of the climate literature nor claims to be comprehensive in terms of literature produced in languages other than English.

Recent growth in the total volume of literature about climate change, and in particular that devoted to impacts and adaptation, has influenced the depth and scope of assessment reports produced by WGII, and it has enabled substantial advances in the assessment of the full range of impacts, adaptation, and vulnerability (Figure 1-1c). The unequal distribution of literature (Figure 1-1a,b,d) presents a challenge to the development of a comprehensive and balanced assessment of the global impacts of climate change. The geographical and topical distribution of literature is influenced by factors such as the availability of funding for scientific research, level of capacity building, regional experience with climate-related disasters, and the availability of long-term observational records.

Literature published on the topic of "climate change" during 1970–1990 focused primarily on changes in the physical climate system and how these changes affected other aspects of the Earth's physical environment.

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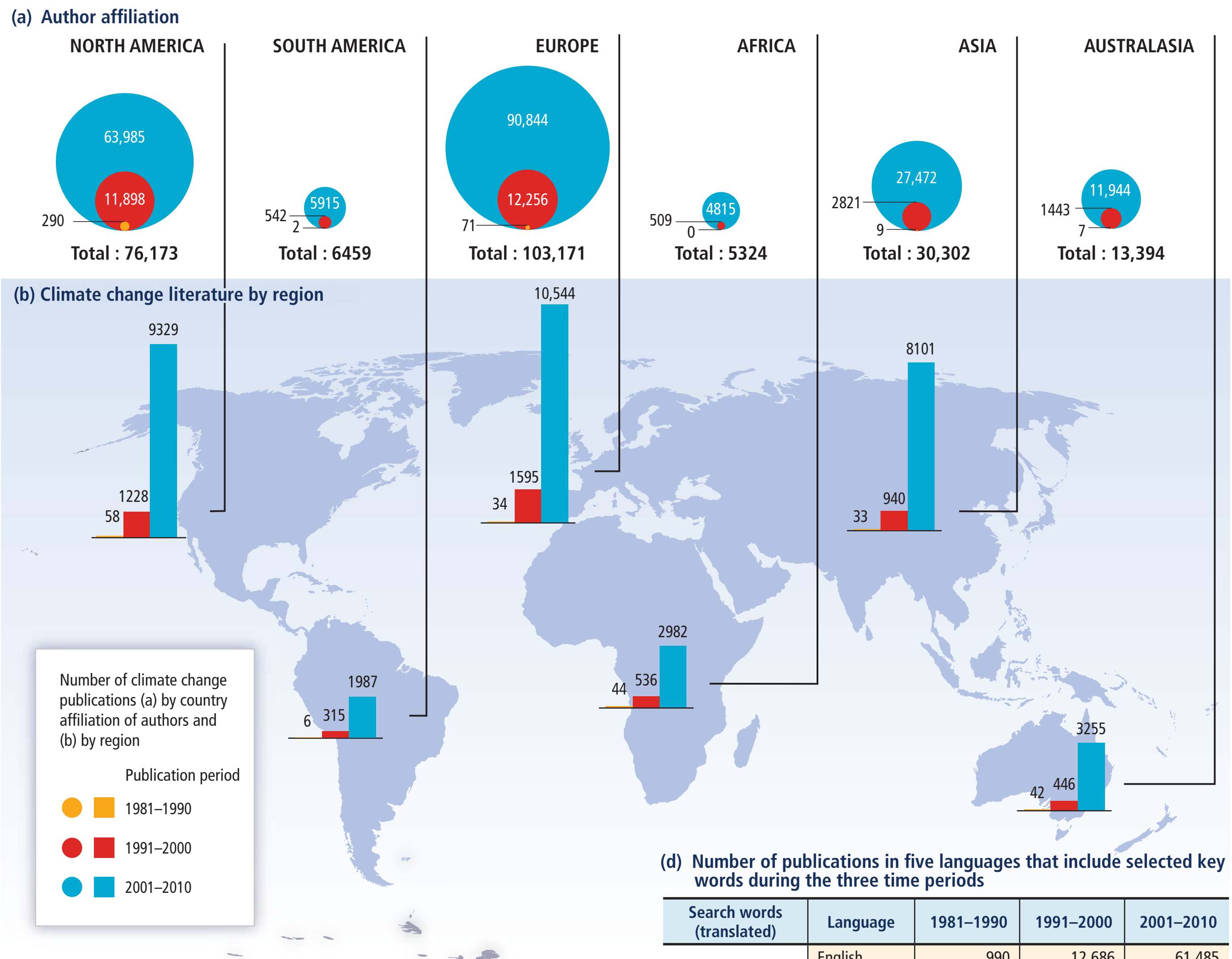
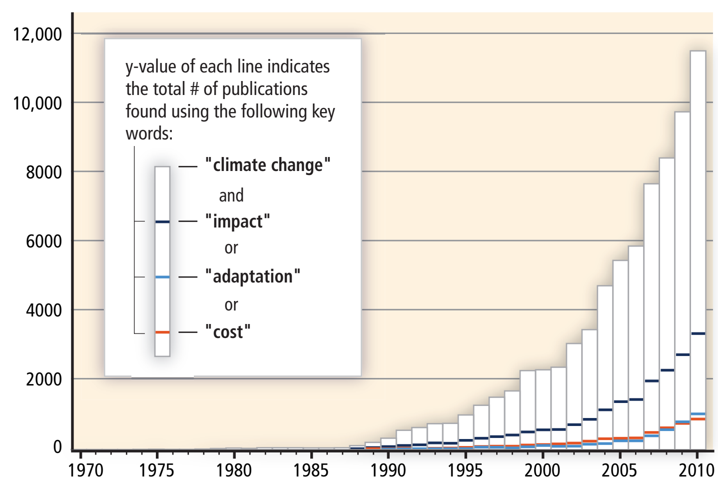
1 Scopus is a bibliographic database owned by Elsevier that contains abstracts and citations for peer-reviewed literature in the scientific, medical, and social sciences (including arts and humanities). Scopus has more than 50 million bibliographic records (about 29 million from 1995 forward and about 21 million from 1823 to 1996), as of September 2013.

2 Web of Science, owned by Thompson Reuters, is a bibliographic database of journals and conference proceedings for the sciences, social sciences, arts, and humanities. Web of Science includes records from over 12,000 journals and 148,000 conference proceedings dating from 1985 to present, as of September 2013.

3 Russia, Greenland, and Iceland are included with Europe; Mexico is included with North America.



(c) Climate change literature in English, total and for selected topics (1970–2010)



(d) Number of publications in five languages that include selected key words during the three time periods

Search words (translated)	Language	1981–1990	1991–2000	2001–2010
"Climate change"	English	990	12,686	61,485
	Chinese	1454	6353	22,008
	French	1	108	815
	Russian	67	210	1443
	Spanish	3	82	1381
"Climate change" and "impacts"	English	232	3001	16,218
	Chinese	133	515	1780
	French	0	1	95
	Russian	0	72	403
	Spanish	0	7	103
"Climate change" and "adaptation"	English	14	373	3661
	Chinese	6	58	321
	French	0	7	110
	Russian	0	7	44
	Spanish	0	5	103
"Climate change" and "cost"	English	24	699	4099
	Chinese	1	22	162
	French	0	7	36
	Russian	0	1	24
	Spanish	0	2	11

Figure 1-1 | Number of climate-change publications listed in the Scopus bibliographic database and results of literature searches conducted in four other languages. (a) Number of publications in English (as of July, 2011) summed by country affiliation of all authors of climate change publications and binned into IPCC regions. Each publication can be counted multiple times (i.e., the number of different countries in the author affiliation list). (b) Number of climate change publications in English with individual countries mentioned in title, abstract, or key words (as of July, 2011) binned into IPCC regions for the decades 1981–1990, 1991–2000, and 2001–2010. Each publication can be counted multiple times if more than one country is listed. (c) Annual global number of publications in English on climate change and related topics: impacts, adaptation, and costs for the years 1970–2010, as of September 2013. (d) Number of publications in five languages that include the words "climate change" and "climate change" plus "adaptation," "impact," and "cost" (translated) in the title, abstract, or key words during the three decades ending in 2010. The following individuals conducted these literature searches during January, 2012–March, 2013: Valentin Przyluski (French), Huang Huanping (Chinese), Peter Zavialov and Vasily Kokorev (Russian), and Saúl Armendáriz Sánchez (Spanish).

Frequently Asked Questions

FAQ 1.1 | On what information is the new assessment based, and how has that information changed since the last report, the IPCC Fourth Assessment Report in 2007?

Thousands of scientists from around the world contribute voluntarily to the work of the IPCC, which was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific assessment of the current scientific literature about climate change and its potential human and environmental impacts. Those scientists critically assess the latest scientific, technical, and socioeconomic information about climate change from many sources. Priority is given to peer-reviewed scientific, technical, and social-economic literature, but other sources such as reports from government and industry can be crucial for IPCC assessments.

The body of scientific information about climate change from a wide range of fields has grown substantially since 2007, so the new assessment reflects the large amount that has been learned in the past 6 years. To give a sense of how that body of knowledge has grown, between 2005 and 2010 the total number of publications just on climate change impacts, the focus of Working Group II, more than doubled. There has also been a tremendous growth in the proportion of that literature devoted to particular countries or regions.

The proportion of climate-change literature in engineering journals has not changed appreciably over the past 4 decades, but there was a significant increase in the proportion of literature published in biological and agricultural science journals. The proportion of the literature on the topic of "climate change" published in social science journals increased from 6% (1970s–1980s) to 9% (1990s–2000s). The themes covered by the literature on vulnerability to climate change have also expanded to issues of ethics, equity, and sustainable development. From the Scopus database, publications on the topic of climate change "impacts" crossed the threshold of 100 per year in 1991. Publications on climate change "adaptation" and societal "cost" reached this level in 2003.

Although authors continue to publish primarily in English, climate-change literature in other languages has also expanded. Literature searches in Chinese, French, Russian, and Spanish revealed a roughly fourfold or greater increase in literature published on the topic of "climate change" in each language during the past 2 decades (Figure 1-1d). Scientists from many countries tend to publish their work in English, as indicated by comparing the regional analysis and country affiliation of authors in Figure 1-1b with the results of the literature searches in the five languages. This process of "scientific internationalism," by which English becomes the primary language of scientific communication, has been described as a growing trend among Russian (Kirchik et al., 2012), Spanish (Alcaide et al., 2012), and French (Gingras and Mosbah-Natanson, 2010) researchers.

1.1.2. Evolution of the Working Group II Assessment Reports and Treatment of Uncertainty

1.1.2.1. Framing and Outlines of Working Group II Assessment Reports

The framing and contents of the IPCC WGII reports have evolved since the First Assessment Report (FAR; IPCC, 1990) as summarized in Figure 1-2. Four characteristics of this evolution are an increasing attention to (1) adaptation limits and transformation in societal and natural systems; (2) synergies between multiple variables and factors that affect sustainable development; (3) risk management; and (4) institutional, social, cultural, and value-related issues. WGII now focuses on understanding the interactions between the natural climate system, ecosystems, human beings, and societies, this being on top of the long-standing emphasis on the biogeophysical impacts of climate change on sectors and regions.

The WGII FAR (296 pages) was organized into six major sectors: agriculture and forestry; terrestrial ecosystems; water resources; human settlements; oceans and coastal zones; and snow, ice, and permafrost. The report focused on the anticipated climate changes for a doubling of carbon dioxide (CO_2). The FAR Summary for Policymakers (SPM) highlighted the coupling of anthropogenic non-climate stresses with climate variability and greenhouse gas (GHG) driven climate change. Given the state of the science in 1990, the FAR has understandably low confidence on some high-vulnerability topics (e.g., global agricultural potential may either increase or decrease), but is more quantitative on large-scale climate impacts (e.g., climatic zones shift poleward by hundreds of kilometers). Health impacts were vague, emphasizing ozone depletion and ultraviolet-B (UV-B) damage. The IPCC WGII 1992 Supplementary Report followed with four assigned topics (regional climate change; energy; agriculture and forestry; sea level rise) and was primarily a strategy report, for example, urging that studies of change in tropical cyclones are of highest priority (IPCC, 1992).

For the IPCC SAR (IPCC, 1996) WGII reviewed climate change impacts, vulnerability, and adaptation plus mitigation options for GHGs. There were two introductory primers, 18 chapters on impacts and adaptation (e.g., forests, rangelands, deserts, human settlements, agriculture, fisheries, financial services, human health), and seven chapters on sectoral mitigation (e.g., energy, industry, forests) but with cost analysis left to WGIII. The SAR made use of the new IPCC 1992 scenarios (IS92). Projections of 2100 sea level rise (15 to 95 cm) and temperature increase (1.0°C to 3.5°C) were similar to the FAR's doubled-CO_2 scenario.

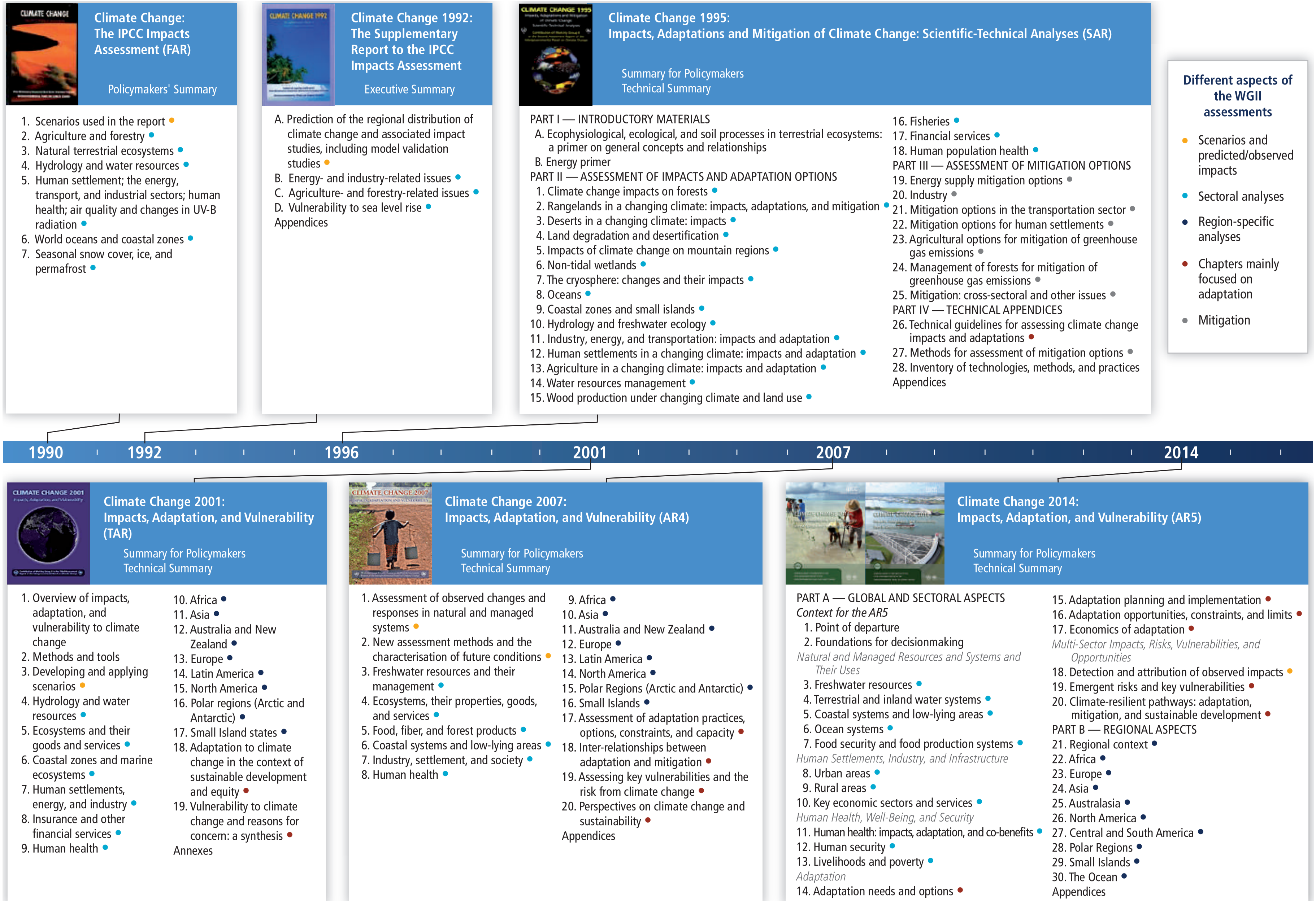


Figure 1-2 | Tables of Contents for the Working Group II contributions to the IPCC Assessments since 1990. The First Assessment Report (FAR; IPCC, 1990) of IPCC Working Group II (WGII) focused on the impacts of climate change. For the Second Assessment Report (SAR; IPCC, 1996) the WGII contribution included mitigation and adaptation with the impacts assessment. With the Third Assessment Report (TAR; IPCC, 2001) and Fourth Assessment Report (AR4; IPCC, 2007) climate change mitigation reverted to WGIII, and WGII remained focused on impacts, adaptation, and vulnerability with an expanded effort on the regional scale.

The SAR notes "Impacts are difficult to quantify, and existing studies are limited in scope; detection [of climate-induced changes] will be difficult," but some specifics are given (e.g., the number of people at risk of flooding from storm surges from sea level rise; the increase in malaria incidence). Vegetation models are used to map out projected changes in major biomes (see WGII SAR SPM Figure 2) – the first prediction figure in a WGII SPM.

WGII TAR (IPCC, 2001b) retained impacts, adaptation, and vulnerability, leaving the topic of mitigation to WGIII. It included five sectoral chapters (water resources, ecosystems, coastal and marine, human settlements and energy, and financial services), eight regional chapters, plus chapters on (1) adaptation, sustainable development, and equity, and (2) vulnerability and reasons for concern. The TAR made the first strong conclusion on attributing impacts: "recent regional climate changes, particularly temperature increases, have already affected many physical and biological systems." Recent increases in floods and droughts, while affecting some human systems, could not be tied to GHG-driven climate change. The TAR introduced the "burning embers" diagram (SPM Figure 2, discussed in Chapters 18 and 19 of this report) as a way to represent "reasons for concern." The adaptive capacity, vulnerability, and key concerns for each region were laid out in detail (SPM, Table 2).

WGII AR4 (IPCC, 2007b,c) retained the basic structure of the TAR with chapters on sectors and regions. The first chapter of AR4, drawing from the expanded literature, provided an "Assessment of Observed Changes in Natural and Human Systems." AR4 incorporated several cross-chapter themes with case studies (such as impacts on deltas) as a unifying construct. Two graphics in the AR4 SPM (SPM Figure 1-2 and Table 1-1) give many examples of projected impacts of climate change, but the state of the science—both of WGI climate projections and WGII impacts—remained too uncertain at the time to give more quantitative estimates of the impacts or necessary adaptation.

This WGII fifth assessment continues and expands the sectoral and regional parts. The AR5 considers a wide and complex range of multiple stresses that influence the sustainability of human and ecological systems. The focus on climate change and related stressors, and the resulting vulnerability and risk, continues throughout this report, including the expanded "reasons for concern" (Chapters 2 and 19; see also Section 1.2.3).

1.1.2.2. Treatment of Uncertainties in IPCC Assessment Reports: A Brief History and Terms Used in the Fifth Assessment Report

An integral feature of IPCC reports is communication of the strength of and uncertainties in scientific understanding underlying assessment findings. Treatment of uncertainties and corresponding use of calibrated uncertainty language in IPCC reports have evolved across IPCC assessment cycles (Swart et al., 2009; Mastrandrea and Mach, 2011). In WGII, the use of calibrated language began in the SAR (1996), in which most chapters used qualitative levels of confidence in Executive Summary findings. With the TAR (2001), formal guidance across the Working Groups was developed (Moss and Schneider, 2000) recognizing that "guidelines such as these will never truly be completed," and an iterative process of learning and improvement of guidance has ensued, informed by experience in each assessment cycle (IPCC, 2005; Mastrandrea et al., 2010). Each subsequent guidance paper has presented related but distinct approaches for evaluating and communicating the degree of certainty in findings of the assessment process.

The AR5 Guidance Note (summarized in Box 1-1) continues to emphasize an overriding theme of clearly linking each key finding and corresponding assignment of calibrated uncertainty language to associated chapter text, as part of the traceable account of the author team's evaluation of evidence and agreement supporting that finding.

1.1.3. Scenarios Used as Inputs to Working Group II Assessments

A scenario is a storyline or image that describes a potential future, developed to inform decision making under uncertainty (Parson et al., 2007). Scenarios have been part of IPCC future climate projections since

Frequently Asked Questions

FAQ 1.2 | How is the state of scientific understanding and uncertainty communicated in this assessment?

While the body of scientific knowledge about climate change and its impacts has grown tremendously, future conditions cannot be predicted with absolute certainty. Future climate change impacts will depend on past and future socioeconomic development, which influences emissions of heat-trapping gases, the exposure and vulnerability of society and ecosystems, and societal capacity to respond.

Ultimately, anticipating, preparing for, and responding to climate change is a process of risk management informed by scientific understanding and the values of stakeholders and society. The Working Group II assessment provides information to decision makers about the full range of possible consequences and associated probabilities, as well as the implications of potential responses. To clearly communicate well-established knowledge, uncertainties, and areas of disagreement, the scientists developing this assessment report use specific terms, methods, and guidance to characterize their degree of certainty in assessment conclusions.

Box 1-1 | Communication of Uncertainty in the Working Group II Fifth Assessment

Based on the 'Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties' (Mastrandrea et al., 2010), the WGII AR5 relies on two metrics for communicating the degree of certainty in key findings:

- Confidence in the validity of a finding, based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and the degree of agreement. Confidence is expressed qualitatively.
- Quantified measures of uncertainty in a finding expressed probabilistically (based on statistical analysis of observations, model results, or expert judgment).

Each finding has its foundation in an author team's evaluation of associated evidence and agreement. The type and amount of evidence available vary for different topics, and that evidence can vary in quality. The consistency of different lines of evidence can also vary. Beyond consistency of evidence, the degree of agreement indicates the consensus within the scientific community on a topic and the degree to which established, competing, or speculative scientific explanations exist.

The Guidance Note provides summary terms to describe the available evidence: *limited*, *medium*, or *robust*; and the degree of agreement: *low*, *medium*, or *high*. These terms are presented with some key findings. In many cases, author teams in addition evaluate their confidence about the validity of a finding, providing a synthesis of the evaluation of evidence and agreement. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*. Figure 1-3 illustrates the relationship between the summary terms for evidence and agreement and the confidence metric. There is flexibility in this relationship; increasing confidence is associated with increasing evidence and agreement, but different levels of confidence can be assigned for a given evidence and agreement statement. The degree of certainty in findings based on qualitative evidence is expressed using levels of confidence and summary terms.

In some cases, available evidence incorporates quantitative analyses, based on which uncertainties can be expressed probabilistically. In such cases, a finding can include calibrated likelihood language or a more precise presentation of probability. The likelihood terms and their corresponding probability ranges are presented below. Use of likelihood is not an alternative to use of confidence: an author team will have a level of confidence about the validity of a probabilistic finding. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high* confidence. When authors evaluate the likelihood of some well-defined outcome having occurred or occurring in the future, the terms and associated meanings are:

Term*	Likelihood of the outcome
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

* Additional terms used more occasionally are *extremely likely*: 95–100% probability, *more likely than not*: >50–100% probability, and *extremely unlikely*: 0–5% probability.

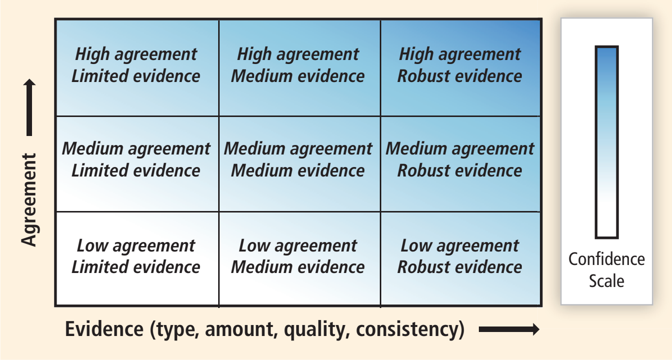


Figure 1-3 | Evidence and agreement statements and their relationship to confidence. The coloring increasing toward the top-right corner indicates increasing confidence. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence.

the FAR (IPCC, 1990), where WGIII generated four scenarios (Bau = business-as-usual, B, C, and D) used by WGI to project climate change. The IPCC Supplementary Report (IPCC, 1992), a joint effort of WGI and WGIII, defined six new scenarios (IS92a–f) used in the SAR (1996). For the TAR (2001), the IPCC *Special Report on Emissions Scenarios* (SRES; Nakicenkovic et al., 2000) created many scenarios from four Integrated Assessment Models (IAMs), out of which a representative range of marker scenarios were selected (A1B, A1T, A1FI, A2, B1, B2). In the SRES, scenarios had had socioeconomic storylines but climate-mitigation options were not included. The SRES scenarios carried over into the AR4 (2007a,b) and formed the basis for the large number of ensemble climate simulations (Coupled Model Intercomparison Project Phase 3 (CMIP3)), which are still in use for climate-change studies relevant to WGII AR5.[4]

With AR5, the development of scenarios fundamentally changed from the IPCC-led SRES process. An ad hoc group of experts, anticipating AR5, built a new structure for scenarios called Representative Concentration Pathways (RCPs) (Moss et al., 2010; van Vuuren et al., 2011) using updated IAMs and intended to provide a flexible, interactive, and iterative approach to climate change scenarios. The four RCPs are keyed to a range of trajectories of GHG concentrations and climate forcing. They are labeled by their approximate radiative forcing (RF, W m^{-2}) that is reached during or near the end of the 21st century (RCP2.6, RCP4.5, RCP6.0, RCP8.5). The quantitative link between the socioeconomic pathway, human activities, and GHG emissions, and subsequently RF, is weaker or nonexistent with current RCP than with SRES scenarios. For example, the RCPs rely on a single parametric model (Meinshausen et al., 2011) to map from emissions to RF, whereas IPCC WGI traditionally assesses this critical linkage using the current state of scientific knowledge (see AR5 WGI Chapters 6, 11, 12, Annex II). In addition, socioeconomic scenarios, emissions, and subsequent radiative forcing pathways were not linked one-to-one in the initial RCPs; however, efforts to derive socioeconomic pathways consistent with each RCP are discussed in Chapter 20.

1.1.3.1. Comparison of RCP and SRES Scenarios

Whereas WGI AR5 is based primarily on results from the RCP CMIP5, the WGII AR5 also uses results from the SRES CMIP3, and thus identifies similar or parallel scenarios from each set. The radiative forcing from the SRES and RCP scenarios is compared in Figure 1-4a. For the latter half of the 21st century, SRES A1FI lies above all RCP and other SRES; SRES A2 has a similar trajectory to RCP8.5 with both reaching about 8 W m^{-2} by 2100; and SRES B1 approximately matches RCP4.5 with both leveling off at about 4 W m^{-2}. RCP6.0 starts similarly to both RCP4.5 and SRES B1, but after 2060 it increases to about 5 W m^{-2}. RCP2.6, a strong mitigation scenario with net CO_2 removal by 2100, falls well outside the SRES range B1 to A2, peaking at about 2.6 W m^{-2} in 2040 and dropping thereafter (WGI AR5 Figure 1-15, Tables AII.6.1 to AII.6.10).

Total RF does not adequately describe the differences in climate change between SRES and RCP scenarios. All RCPs adopted stringent air pollution mitigation policies and thus have much lower tropospheric ozone and aerosol abundances than the SRES scenarios, which ignored the role of air quality regulations (WGI AR5 Tables AII.2.16 to AII.2.22). In terms of ozone and particulate matter precursor emissions, there is almost no overlap between SRES and RCP scenarios (WGI AR5 Tables AII.2.16 to AII.2.22). In terms of surface ozone at the continental scale, after 2060 the RCPs are similar to low-end SRES B1 (WGI AR5 Tables AII.7.1 and AII.7.2).

Global mean surface temperature change for these scenarios is shown in Figure 1-4b, based on WGI AR5 (Chapters 11, 12; Tables AII.7.5 and AII.7.6) and WGI AR4 (Figure 10.26). For purposes here, that is, of understanding differences in impact studies using different scenarios, only model CMIP5 ensemble means are shown for the RCPs. If the standard deviation of the models were plotted, all RCPs would touch or overlap through the century (WGI AR5 Table AII.7.5), but even this range underestimates the uncertainties in temperature change for those scenarios (see WGI AR5 Chapter 12). The AR5 RCP data are taken directly from the CMIP5 runs, whereas the AR4 data are based on a simple model, parameterized to match the different CMIP3 models (see Figure 1-4 caption). In terms of temperature change, RCP8.5 is close to SRES A2, but below SRES A1FI. RCP4.5 follows SRES B2 up to 2060, but then drops to track SRES B1. RCP6.0 has lower temperature change to start, following SRES B1, but then increases toward SRES B2 by 2100. In general, scenarios SRES A1B, A1T, and B2 lie in the large gap between RCP8.5 and RCP4.5/6.0. The RCP2.6 temperature change stabilizes at about 1°C above the reference period (1986–2005). The other RCPS and all SRES scenarios span the range 1.8°C to 4.1°C for the 2090s. The CMIP5 reference period is about 0.6°C above earliest observing period 1850–1900 (WGI AR5 Chapter 2).

1.1.3.2. Shared Socioeconomic Pathways

Shared Socioeconomic Pathways (SSPs) are being generated (Arnell et al., 2011; Kriegler et al., 2012) to form more complete scenarios that link each RCP's climate path to a range of human development pathways. The SSPs include three elements: (1) storylines, which are descriptions of the state of the world; (2) IAM quantitative variables (such as population, gross domestic product (GDP), technology availability); and (3) other variables, not included in the IAMs, such as ecosystem productivity and sensitivity or governance index. With these elements a goal of the SSP effort is to characterize a global socioeconomic future for the 21st century as a reference for climate change analysis (O'Neill et al., 2012). Combined SSP–RCP scenarios are needed to support synthesis across all IPCC Working Groups and, particularly for WGII, to facilitate the use of new climate modeling results with impacts, adaptation, and vulnerability (IAV) research. Five basic SSPs have been proposed, representing a wide range of possible development pathways,

[4] The Coupled Model Intercomparison Project is an activity of the World Climate Research Programme's Working Group on Coupled Modelling. Climate model output from simulations of the past, present, and future climate archived mainly in 2005–2006 constituted Phase 3 of the Coupled Model Intercomparison Project (CMIP3). Similar climate simulations by an expanded set of models with a close off date of March 2013 are being used in AR5 and constitute Phase 5 of the project (CMIP5). CMIP3 used the SRES scenarios, and CMIP5 used the Reference Concentration Pathway (RCP) scenarios.

primarily at global or large regional scales. For each RCP it is expected that one or more SSP could lead to that climate path. Several chapters of this report refer to the SSPs in their discussion of analyses of future impacts and vulnerability. Chapter 20 (Section 20.6.1) describes SSPs in more detail, and Chapter 21 (Section 21.2.2) notes how the time lags in producing SSPs has limited the use of CMIP5–RCP scenarios in AR5.

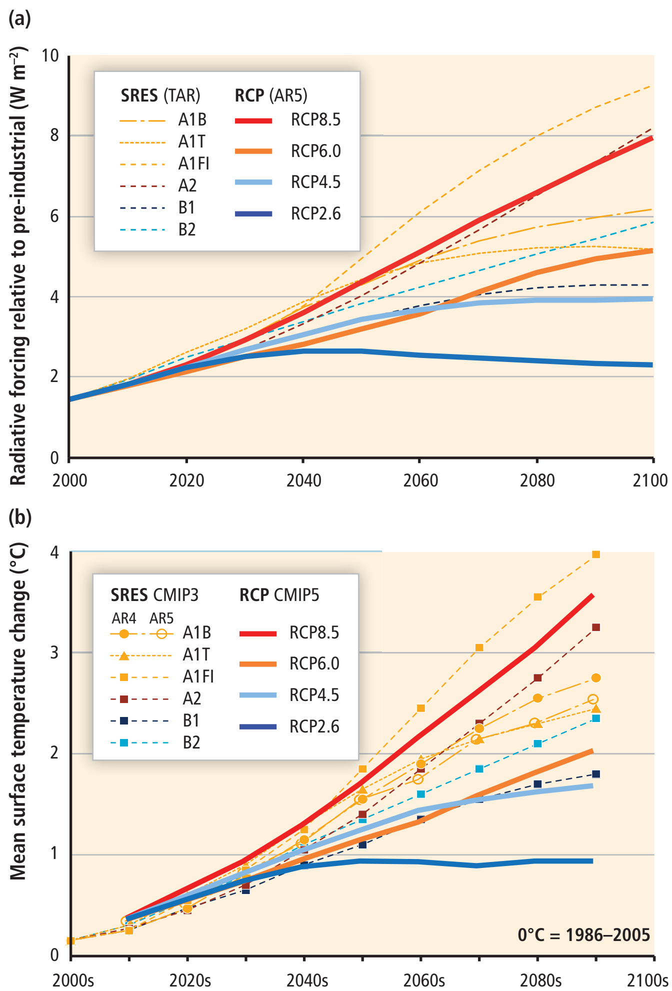


Figure 1-4 | (a) Projected radiative forcing (RF, $W m^{-2}$) and (b) global mean surface temperature change (°C) over the 21st century using the Special Report on Emissions Scenarios (SRES) and Representative Concentration Pathway (RCP) scenarios. RF for the RCPs are taken from their published CO_2-equivalent (Meinshausen et al., 2011), and RF for SRES are from the Third Assessment Report Appendix II (Table II.3.11). For RF derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) models, see WGI (Section 12.3; Tables AII.6.9, 6.10). The ensemble total effective RF at 2100 for CMIP5 concentration-driven projections are 2.2, 3.8, 4.8, and 7.6 $W m^{-2}$ for RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively. The SRES RF are shifted upward by 0.12 $W m^{-2}$ to match the RCPs at year 2000 because the climate change over the 21st century is driven primarily by the changes in RF and the offset is due primarily to improvements in model physics including the aerosol RF. For more details and comparison with pre-SRES scenarios, see WGI AR5 Chapter 1 (Figure 1-15). Temperature changes are decadal averages (e.g., 2020s = 2016–2025) based on the model ensemble mean CMIP5 data for the RCPs (colored lines). The same analysis is applied to CMIP3 SRES A1B (yellow circles). See WGI AR5 Chapters 11, 12; Table AII.7.5. The colored squares show the temperature change for all six SRES scenarios based on a simple climate model tuned to the CMIP3 models (WGI AR4 Figure 10.26). The difference between the yellow circles and yellow squares reflects differences between the simple model and analysis of the CMIP3 model ensemble in parallel with the CMIP5 data. For an assessment of uncertainties and *likely* ranges of temperature change, see WGI AR5 Figures 11.24, 11.25, 12.4, 12.5, 12.40.

1.1.4. Evolution of Understanding the Interaction between Climate Change Impacts, Adaptation, and Vulnerability with Human and Sustainable Development

The continuing increase in GHG emissions has highlighted the commitment to climate change and its varied impacts and has contributed to an increasing emphasis on vulnerability, adaptation, and sustainability. The possible range of socioeconomic trajectories in countries with low, medium, high, and very high human development is among the largest sources of uncertainty in scenario building and climate projections. A deeper understanding of development patterns, adaptation limits, and maladaptation, as well as options for more climate resilient pathways, has helped identify a larger range of potential climate change impacts and the risks they pose to society.

The first three WGII reports focused primarily on characterizing the biophysical impacts of climate change, with a progressively more elaborated understanding of economic and social impacts. The literature of the last decade indicates a more integrated understanding of the physical and social impacts of climate change. The extent and structure of WGII AR5 shows such advancements. The AR4 Synthesis Report asserted that "climate change impacts depend on the characteristics of natural and human systems, their development pathways and their specific locations" (IPCC, 2007d, p. 64). WGII AR4 Chapter 20 offered a catalog of multiple stresses jointly impacting people and communities and also highlighted questions of justice and equity in shaping development pathways in the context of climate change.

1.1.4.1. Vulnerability and Multiple Stressors

Climate-related risks interact with other biophysical and social stressors. Vulnerability is defined in the WGII TAR Glossary in terms of susceptibility and as a "function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity." Since then, the understanding of vulnerability has acquired increased complexity as a multidimensional concept, with more attention to the relation with structural conditions of poverty and inequality. WGII AR5 defines vulnerability simply as the propensity or predisposition to be adversely affected, and many chapters identify such vulnerabilities through societal risks, particularly in low-income economies. Recent studies suggest that climate impacts could slow down or reverse past development achievements; hinder global efforts on poverty reduction; and lead to human and environmental insecurity, displacement and conflict, maladaptation, and negative synergies (Jerneck and Olsson, 2008; Boyd and Juhola, 2009; Barnett and O'Neill, 2010; Ogallo, 2010; see also Sections 3.5.1, 8.2.4, 12.2.1, 12.4.1, 12.5.1, 13.2.1, 14.7).

The concept of resilience emerged from ecological sciences and has been increasingly used by social sciences. In climate change literature it describes the ability of a system to respond to disturbances, self-organize, learn, and adapt (Turner, 2010; Brown, 2013; WGII AR5 Glossary). Vulnerability, adaptation, and resilience are determined by multiple stressors, a combination of biophysical and social factors that jointly determine the propensity and predisposition to be adversely affected. For example, adaptive capacity in many urban centers in less

Frequently Asked Questions

FAQ 1.3 | How has our understanding of the interface between human, natural, and climate systems expanded since the 2007 IPCC Assessment?

Advances in scientific methods that integrate physical climate science with knowledge about impacts on human and natural systems have allowed the new assessment to offer a more comprehensive and finer-scaled view of the impacts of climate change, vulnerabilities to those impacts, and adaptation options, at a regional scale. That's important because many of the impacts of climate change on people, societies, infrastructure, industry, and ecosystems are the result of interactions between humans, nature, and specifically climate and weather, at the regional scale.

In addition, this new assessment from Working Group II greatly expands the use of the large body of evidence from the social sciences about human behavior and the human dimensions of climate change. It also reflects improved integration of what is known about physical climate science, which is the focus of Working Group I of the IPCC, and what is known about options for mitigating greenhouse gas emissions, the focus of Working Group III. Together this coordination and expanded knowledge inform a more advanced and finer-scaled, regionally detailed assessment of interactions between human and natural systems, allowing more detailed consideration of sectors of interest to Working Group II such as water resources, ecosystems, food, forests, coastal systems, industry, and human health.

developed countries is constrained by poverty, unemployment, quality of housing, or lack of access to potable water, sanitation, health care, and education interacting with land degradation, water stress, or biodiversity loss (Sections 8.2.4, 11.6.2, 22.4.4). Adaptation options and limits for high-end warming scenarios are often contextualized in relation to socioeconomic vulnerabilities and other stressors (Gupta et al., 2010; New et al., 2010; Stafford Smith et al., 2011; Brown, 2012; World Bank, 2012; see also Section 16.4.2.4).

1.1.4.2. Adaptation, Mitigation, and Development

Impacts of climate change will vary across regions and populations, through space and time, dependent on myriad factors including non-climate stressors and the extent of mitigation and adaptation. Changes in both climate and development are key drivers of the core components of risk (exposure, vulnerability, and physical hazards). The relations with development are complex and contested. There is disagreement about fundamental issues, such as the compatibility of development goals and climate change mitigation, the prioritization of responses (reducing consumption versus investment in sustainable technologies), and the stage of development at which countries should take action (see Box 1-2 for terms used to characterize stages of development) (Schipper, 2007; Grist, 2008; Brooks et al., 2009). The literature points to how inequalities, trade imbalances, intellectual property rights, gender injustice, or agricultural systems, *inter alia*, cannot be addressed with development focusing solely on increasing economic growth (Pogge, 2008; McMichael, 2009; Alston, 2011; UNDP, 2007, 2011; Büscher et al., 2012; OECD, 2013).

The recent literature shows increasing attention to questions of ethics, justice, and responsibilities relating to climate change (Timmons and Parks, 2007; O'Brien et al., 2010; Pelling, 2010; Arnold, 2011; Gardiner, 2011; Caney, 2012; Marino and Ribot, 2012). As basic resources such as energy, land, food, or water become threatened, inequalities and unfairness may deepen, leading to maladaptation and new forms of vulnerability. Responses to climate change may have consequences and outcomes that favor certain populations or regions. For example, there are increasing cases of land-grabbing and large acquisitions of land or water rights for industrial agriculture, mitigation projects, or biofuels that have negative consequences on local and marginalized communities (Borras et al., 2011; see also Section 14.7). Ethical perspectives are also important in relation to adaptation constraints and limits (see Section 16.7) and mitigation (see Section 1.3.4 and WGIII AR5).

Climate change impacts have become a central issue in the work of developmental organizations such as the United Nations specialized agencies, bilateral donor institutions, and non-governmental organizations (NGOs) that link adaptation concerns with ongoing development efforts. The increase in adaptation literature and experience, however, has led to the development of adaptation policies in many parts of the world, as reflected in four chapters here devoted to adaptation (14 to 17) and all of the regional chapters of this report. At the policy level, individual country National Adaptation Programmes of Action and National Communication reports to the United Nations Framework Convention on Climate Change (UNFCCC) had in the past focused primarily on physical climate change drivers and impacts. An analysis of National Communications documents submitted through 2004 by many of the Annex 1 countries, for example, showed that climate change impacts and adaptation receive very limited attention relative to the discussion of GHG emissions and mitigation policies (Gagnon-Lebrun and Agrawala, 2006). However, concern and actual progress toward adaptation is evident in Latin America (Gutierrez and Espinosa, 2010) and in recent National Communications of some non-Annex 1 countries, such as India (2012) and Iran (2010), which devoted a substantive part of their recent reports to the topic of adaptation.

Some researchers and institutions have sought to identify a continuum between development, adaptation strategies, and financing, including increasing attention to co-benefits with mitigation (USAID, 2008; Heltberg et al., 2009; Mearns and Norton, 2010; World Bank, 2010; Richardson et al., 2011; OECD, 2013). "Greener" development and market-based mechanisms are being explored as instruments to achieve synergies

Box 1-2 | Country Development Terminology

There are diverse approaches for categorizing countries on the basis of their level of development and for defining terms such as industrialized, developed, or developing. Table 1-1 presents selected categorizations used in this report. In the United Nations system, there is no established convention for the designation of developed and developing countries or areas (UN DESA, 2012). The United Nations Statistics Division specifies developed and developing regions based on "common practice." In addition, specific countries are designated as least developed countries, landlocked developing countries, small island developing states, and transition economies. Many countries appear in more than one of these categories. The World Bank uses income as the main criterion for classifying countries (World Bank, 2013). The UNDP aggregates indicators for life expectancy, educational attainment, and income into a single composite Human Development Index (HDI) (UNDP, 2013).

Table 1-1 | Selected country development categorizations used in this report.

Categorization approach	Categories	Criteria	Reference
United Nations	• Developing regions • Developed regions	Common practice	UN DESA (2012)
	Least developed countries	• Gross National Income (GNI) per capita • Human assets • Economic vulnerability to external shocks	UN DESA (2008)
	Landlocked developing countries	• Lack of territorial access to the sea • Remoteness and isolation from world markets • High transit costs	UN (2003)
	Small island developing states	Low-lying coastal countries sharing similar socioeconomic and environmental vulnerabilities	UN (1993)
	Economies in transition/transition economies	Countries changing from central planning to free markets	UN DESA (2013)
World Bank	• Low income • Lower middle income • Upper middle income • High income	GNI per capita	World Bank (2013)
UNDP	• Low human development • Medium human development • High human development • Very high human development	• GNI per capita • Life expectancy at birth • Mean years of schooling • Expected years of schooling	UNDP (2013)

between mitigation and adaptation efforts, development financing, and planning, and links to energy needs are some of the instruments explored. Large concerns remain, however, about the preconditions needed for market mechanisms to work as intended, the problems of carbon leakage, and the potential negative effects of some mitigation strategies (Liverman, 2010; see also Section 13.1.3 and WGIII AR5 Chapter 15).

1.1.4.3. Transformation and Climate-Resilient Pathways

Transformation—a change in the fundamental attributes of a system including altered goals or values—has emerged as a key concept in describing the dimensions, types, and rates of societal response to climate change. In the context of adaptation, we can distinguish between incremental and transformative adaptation, the latter referring to changes in the fundamental attributes of a system in response to climate change and its effects (WGII AR5 Glossary; Park et al., 2012). The *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) recognized transformation in technological, financial, regulatory, legislative, and administrative systems (IPCC, 2012; see Sections 1.3.1, 20.5). Recent literature points to changes in values, norms, belief systems, culture, and conceptions of progress and well-being as either facilitating or preventing transformation (Pelling, 2010; Stafford Smith et al., 2011; Kates et al., 2012; O'Brien, 2013). Transformation of this nature requires a particular understanding of risks, adaptive management, learning, innovation, and leadership, and may lead to climate resilient development pathways (see Section 1.2.3 and Chapter 20). Transformational change is not called for in all circumstances (Pelling, 2010) and in some cases may lead to negative consequences for some locations or social groups, contributing to social inequities (O'Brien, 2013). Climate resilient pathways include actions, strategies, and choices that reduce climate change impacts while assuring that risk management and adaptation can be implemented and sustained.

1.1.4.4. The Opportunity Space for Decision Making

Recognizing the need for policy-relevant science, much scientific activity tends to be coordinated through international programs that focus on, for example, biodiversity, desertification, food security, impacts on social practices and institutions, and monitoring sea level rise. The trend in research is to create synergies across the sciences by including social and human sciences perspectives and transdisciplinarity. The production of information with non-scientific sources such as indigenous knowledge or stakeholder views is also enriching climate change research. This trend has led to the merging of relevant global programs of the international councils for science and for social science (ICSU and ISSC) under the umbrella "Future Earth" (see also ISSC and UNESCO, 2013). This expanded scientific focus combined with increased practice and experience with adaptation creates a new opportunity space for evaluating policy options and their risks in the search for climate resilient development pathways (Figure 1-5) (Sections 2.1, 2.4.3, 20.2, 20.3.3). Human and social-ecological systems can build resilience through adaptation, mitigation, and sustainable development.

Over the next few decades, global temperatures are projected to increase along broadly similar pathways, whether or not mitigation of GHGs occurs (Section 1.3.3). During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate and societal responses, including adaptation, will influence near-term outcomes. In the second half of the 21st century and beyond, global temperature increases diverge across emissions scenarios. During this longer term era of climate options, near-term and ongoing mitigation efforts as well as development trajectories will determine the risks associated with climate change.

1.2. Major Conclusions of the Working Group II Fourth Assessment Report

This section presents highlights of the IPCC Fourth Assessment Report that are particularly relevant to AR5 as a point of departure. These highlights are drawn from the AR4 Synthesis Report, the WGII AR4

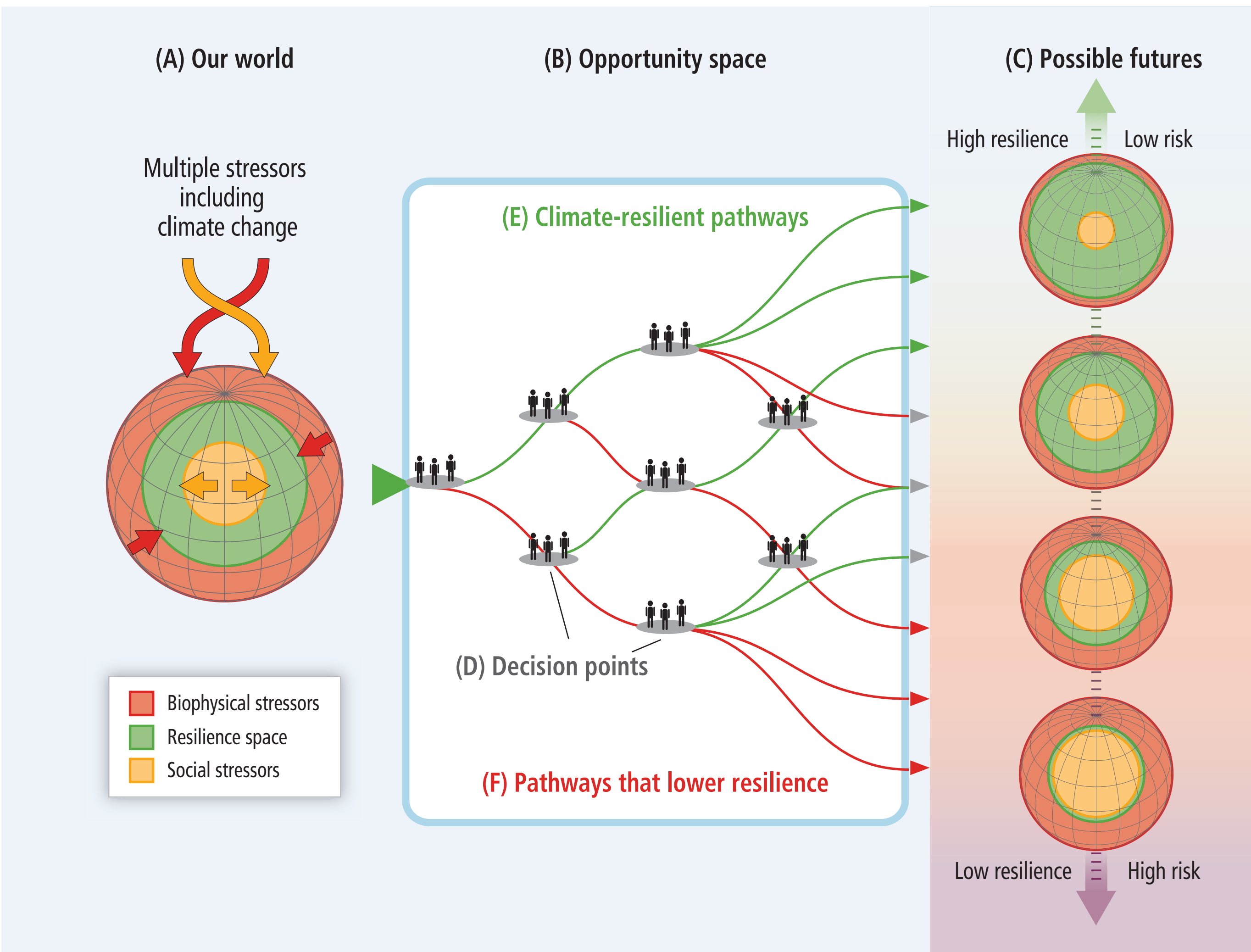


Figure 1-5 | Opportunity space and climate-resilient pathways. (a) Our world is threatened by multiple stressors that impinge on resilience from many directions, represented here simply as biophysical and social stressors. Stressors include climate change, climate variability, land-use change, degradation of ecosystems, poverty and inequality, and cultural factors. (b) Opportunity space refers to decision points and pathways that lead to a range of (c) possible futures with differing levels of resilience and risk. (d) Decision points result in actions or failures-to-act throughout the opportunity space, and together they constitute the process of managing or failing to manage risks related to climate change. (e) Climate-resilient pathways (in green) within the opportunity space lead to a more resilient world through adaptive learning, increasing scientific knowledge, effective adaptation and mitigation measures, and other choices that reduce risks. (f) Pathways that lower resilience (in red) can involve insufficient mitigation, maladaptation, failure to learn and use knowledge, and other actions that lower resilience; and they can be irreversible in terms of possible futures.

Summary for Policymakers (SPM), and the WGII AR4 chapter Executive Summaries.

1.2.1. Observed Impacts

Evidence presented in WGII AR4 Chapter 1 indicated that physical and biological systems on all continents and in most oceans were being affected by recent climate changes, particularly regional temperature increases (Rosenzweig et al., 2007, p. 81). In terrestrial ecosystems, warming trends were consistent with observed change in the timing of spring events and poleward and upward shifts in plant and animal ranges. The authors found that the geographical locations of observed changes during the period 1970–2004 are consistent with spatial patterns of atmospheric warming. The types of hydrologic changes reported included effects on snow, ice, and frozen ground; the number and size of glacial lakes; increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers; thermal structure and water quality of rivers and lakes; and more intense drought and heavy rains in some regions. The authors concluded from a synthesis of studies "that the spatial agreement between regions of significant warming and the locations of significant observed changes is *very unlikely* to be due solely to natural variability of temperatures or natural variability of the systems" (IPCC, 2007c, p. 9).

Observed regional impacts to human systems were less obviously attributed to anthropogenic climate change. AR4 authors concluded that **"There is *medium confidence* that other effects of regional climate change on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers"** (IPCC, 2007d, p. 3). They presented evidence on the effects of temperature increases on agricultural and forest management at Northern Hemisphere (NH) higher latitudes (e.g., earlier spring planting of crops, alterations in disturbance regimes of forests due to fires and pests); on some aspects of human health (e.g., heat-related mortality in Europe, changes in infectious disease vectors in some areas, and allergenic pollen in NH high and mid-latitudes); and some human activities in the Arctic (e.g., hunting and travel over snow and ice) and in lower-elevation alpine areas (such as mountain sports).

The authors of AR4 concluded that "Recent climate changes and climate variations are beginning to have effects on many other natural and human systems. However, based on published literature, the impacts have not yet become established trends" (IPCC, 2007c, p. 9). Three examples were cited: in mountain regions melting glaciers enhanced risk of glacier lake outburst floods on settlements; in the Sahelian region of Africa warmer and drier conditions had detrimental effects on some crops; and in coastal areas sea level rise and human development contributed to losses of coastal wetlands and mangroves and to increases in damage from coastal flooding.

1.2.2. Key Vulnerabilities, Risks, and Reasons for Concern

In an effort to provide some insights into the seriousness of the impacts of climate change WGII TAR (Chapter 19) identified five "Reasons for Concern" (RFC) focusing on (1) unique and threatened systems, (2) extreme climate events, (3) distribution of impacts, (4) aggregate impacts, and (5) large-scale discontinuities (see Figure SPM-2 in IPCC, 2001b). Considering new evidence of observed changes on every continent, coupled with more thorough understanding of the concept of vulnerability, the AR4 concluded that the five "reasons for concern identified in the TAR remained a viable framework to consider key vulnerabilities" (IPCC, 2007d, p. 19).

The AR4 Synthesis Report SPM concluded with the following key message: **Responding to climate change involves an iterative risk management process that includes both adaptation and mitigation and takes into account climate change damages, co-benefits, sustainability, equity and attitudes to risk** (IPCC, 2007d, p. 22). The concept of risk (the confluence of likelihood and consequence) is the focus of this AR5 Report. All chapters, especially 2, 18, and 19, now focus on climate change, related stressors, resulting vulnerabilities, and associated risks. Correlating the risk-based framing of the RFC in WGII AR5 with the conclusions reported in the AR4 SPM is straightforward (italics indicate new terms that have been added to the RFC definitions from the IPCC, 2007d, p. 19):

- Risks to Unique and Threatened Systems: "There is new and stronger evidence of observed impacts of climate change on unique and vulnerable systems (such as polar and high mountain communities and ecosystems), with increasing levels of adverse impacts as temperatures increase."
- *Risks Associated with* Extreme Weather Events: "Responses to some recent extreme events reveal higher levels of vulnerability than the TAR. There is now higher confidence in the projected increases in droughts, heat waves, and floods, as well as their adverse impacts."
- *Risks Associated with the* Distribution of Impacts: "There are sharp differences across regions and those in the weakest economic position are often the most vulnerable to climate change. There is increasing evidence of greater vulnerability of specific groups such as the poor and elderly not only in developing but also in developed countries. Moreover, there is increased evidence that low-latitude and less developed areas generally face greater risk, for example, in dry areas and megadeltas."
- *Risks Associated with* Aggregate Impacts: "Compared to the TAR, initial net market-based benefits from climate change are projected to peak at a lower magnitude of warming, while damages would be higher for larger magnitudes of warming."
- Risks Associated with Large-Scale Discontinuities: "There is high confidence that global warming over many centuries would lead to a sea level rise contribution from thermal expansion alone that is projected to be much larger than observed over the 20th century, with loss of coastal area and associated impacts. There is better understanding than in the TAR that the risk of additional contributions to sea level rise from both the Greenland and possibly Antarctic ice sheets may be larger than projected by ice sheet models and could occur on century time scales."

WGII AR5 Chapters 18 and 19 recognize new evidence about the RFC in the context of risk. Chapter 18 expands our understanding of how observed and attributed impacts, vulnerabilities, and associated risks support the identification of the dependence of the RFC on temperature "up to the present." Chapter 19 extends this analysis to future temperatures. Both chapters demonstrate how accounting for both components of risk in assessing the RFC permits a clearer understanding of "key vulnerabilities."

1.2.3. Interaction of Adaptation and Mitigation in a Policy Portfolio

A conclusion of AR4 is that coping with risks of climate change will involve a portfolio of initiatives that will evolve iteratively over time as new information about the workings of the climate system and new insights into how various responses are actually working and penetrating the global socioeconomic structure. The WGII AR4 concluded that (1) neither adaptation nor mitigation alone can avoid all climate change impacts, though together they can significantly reduce the risks of climate change; (2) adaptation is necessary in the short and longer term to address impacts, even for the lowest stabilization scenarios assessed, but there are barriers, limits, and costs, though these are not fully understood; (3) unmitigated climate change would *likely* exceed the adaptive capacity of natural, managed, and human systems in the long term; and (4) while many impacts can be reduced, delayed, or avoided by mitigation, delayed emission reductions "significantly constrain the opportunities to achieve lower stabilization levels and increase the risk of more severe climate change impacts." (IPCC, 2007d, p. 19).

WGII AR5 devotes considerable attention to the interface of adaptation and mitigation and the mechanisms for iterating decisions as described in a collection of chapters (16, 17, 19, and 20) designed explicitly for this purpose. These chapters build substantially upon key messages from the AR4 chapter entitled "Inter-relationships between adaptation and mitigation" (IPCC, 2007b, p. 747), including:

- Even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, which makes adaptation unavoidable.
- Without mitigation, a magnitude of climate change is likely to be reached that makes adaptation impossible for some natural systems, while for most human systems it would involve very high social and economic costs.
- **"Creating synergies between adaptation and mitigation can increase the cost-effectiveness of actions and make them more attractive to stakeholders, including potential funding agencies (medium confidence)."** Such synergies, however, provide no guarantee that resources are used in the most efficient manner and opportunities for synergies are greater in some sectors (e.g., agriculture and forestry) than others (e.g., energy, health, and coastal systems).
- **"It is not yet possible to answer the question as to whether or not investment in adaptation would buy time for mitigation (high confidence)."** Barriers to understanding the trade-offs of the immediate benefits of localized adaptation and the longer term global benefits of mitigation, coupled with the limitation of models to simulate the intricacies of the interactions of the two, present a challenge to designing and implementing an "optimal mix" of response strategies.
- **"People's capacities to adapt and mitigate are driven by similar sets of factors (high confidence).** These factors represent a generalized response capacity that can be mobilized for both adaptation and mitigation." The authors noted that even societies with high adaptive capacity can be vulnerable to climate change, variability, and extremes.

1.3. Major Conclusions of More Recent IPCC Reports

Since publication of the AR4 in 2007, the IPCC has produced two Special Reports: the *Special Report on Renewable Energy Sources and Climate Change Mitigation*, produced by Working Group III and published in 2011; and the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, produced jointly by WGI and WGII and published in 2012. In addition, the AR5 cycle has staggered the assessment work for its three working groups. WGI AR5 was released in September 2013, and WGIII AR5 will be published after WGII AR5 in 2014. In this section we summarize the major conclusions of the SREX, the SRREN, WGI AR5, and preliminary findings from WGIII AR5. We focus on the key findings, framings, and conceptual innovations these reports bring to WGII AR5.

One common theme that cuts across the Working Groups is the connection of three basic elements of climate change: (1) detection of climate change or its impacts; (ii) attribution of that observed climate change to the increases in GHGs (i.e., human cause, WGI) or attribution of local impacts to the observed climate change in that region; and (3) projection of these impacts and climate change into the 21st century. Table 1-2 gives a summary of phenomena for which such detection,

Trend

- ^ Increasing overall
- v Decreasing overall
- More regions increasing than decreasing
- More regions decreasing than increasing
- ~ Regionally varies or no clear trend

Attribution

- Attributable to observed climate change (red)
- Attributable to human influence (blue)

Projected

- Occurs in 21st century (orange)

Confidence assessment

HC	***High*** or ***Very High*** confidence
MC	***Medium*** confidence
LC	***Low*** confidence
X	***Very low*** confidence or No formal confidence level given
–	No explicit assessment made

Findings assigned a likelihood term are associated with high or very high confidence.

Likelihood assessment

****	*Virtually certain 99–100%*
***	*Extremely likely 95–100%*
**	*Very likely 90–100%*
*	*Likely 66–100%*

Table 1-2 | Confidence in the observation, attribution, and projection of changes in climate system phenomena.

	Phenomenon	Change	Observed to 2010 (X-axis, Figure 1-6)	Y-axis, Figure 1-6		Source
				Attribution	Projected 2050-2100	
1	Greenhouse gases: CO_2, CH_4, N_2O	^	****	****	**** (RCPs: CO_2,N_2O)	AR5 I-2, I-10, I-11, I-12
2	Global Mean Surface Air Temperature (GMST)	^	****	***	****	AR5 I-2, I-10, I-11, I-12
3	GMST over all continents except Antarctica	^	****	*	****	AR5 I-2, I-10, I-11, I-12
4	Global mean sea level	^	****	**	****	AR5 I-3, I-10, I-13
5	Arctic sea ice cover	v	****	**	**	AR5 I-4, I-10, I-11, I-12
6	Hot days and nights over land (warmth, frequency)	^	**	**	****	AR5 SPM-1
7	Cold days and nights over land (warmth, frequency)	v	**	**	****	AR5 SPM-1
8	Extreme high sea level (incidence, magnitude)	^	* (since 1970)	X	**	AR5 SPM-1
9	Heat waves and warm spells over land (frequency, duration)	◊	*MC*	*	**	AR5 SPM-1
10	Heavy precipitation events	◊	*	*MC*	**	AR5 I-2, I-10, I-12
11	Drought (intensity, duration)	◊	*MC* (some regions)	*LC*	*	AR5 SPM-1, SREX-4
12	Tropical cyclones (intensity, frequency, some basins)	~	*LC*	*LC*	MC (intensity increase, some basins)	AR5 SPM-1
13	Global mean precipitation	^	*LC*	*LC*	****	AR5 I-2, I-10, I-11, I-12
14	Contrast between wet and dry regions	^	X	X	HC	AR5 I-12
15	Snow cover (Northern Hemisphere, extent)	v	HC	HC	HC	AR5 I-4, I-10, I-12
16	Permafrost regions (degrade)	v	MC	X	MC	AR5 I-4, I-12
17	Storm tracks (shift poleward)	^	*	X	*	AR5 I-2, I-12
18	Wave heights (different oceans)	^	MC (N. Atlantic)	X	** (Arctic a) * (Southern b)	AR5 I-3, I-13
19	Upper ocean (warming)	^	****	***	***	AR5 I-3, I-10, I-11, I-12
20	Ocean acidification	^	****	***	****	AR5 I-3, I-10, I-6
21	Oceanic oxygen	v	*MC*	*MC*	**	AR5 I-3, I-10, I-6
22	Floods (magnitude, frequency)	~	*LC*	*LC*	*LC*	SREX-3
23	Mountain phenomena (slope instabilities, mass movement, glacial lake outbursts)	^	*HC*	*HC*	*HC*	SREX-3, AR4 SyR
24	Monsoons	~	*LC*	*LC*	*LC*	SREX-3
25	Plant and animal species (move poleward or up in altitude)	^	*HC*	*HC*	*HC*	AR4 II-SPM, AR4-SyR
26	Mountain phenomena (slope instabilities, mass movement, glacial lake outbursts)	^	*HC*	*HC*	*HC*	SREX-3, AR4 SyR
27	Timing of spring events (earlier leafing, greening, planting, bird migration, etc.)	^	*HC*	*HC*	*HC*	AR4 SyR
28	Marine/freshwater biological systems (shifts in algal, plankton, and fish ranges)	~	*HC*	*HC*	*HC*	AR4 SyR
29	Human health (heat-related mortality, infectious disease vectors)	^	*MC*	MC	X	AR4 SyR
30	Water resources	v	X	X	*HC* (many regions)	AR4 SyR-SPM
31	Mountain glaciers	v	*HC*	X	*HC*	AR4 II-SPM
32	Coral degradation, bleaching	^	*HC*	–	*HC*	AR4 II-SPM, SyR-SPM
33	Economic losses from weather- and climate-related disasters	^	*HC*	X	*HC*	SREX-4
34	Annual costs of climate change	^	X	X	**	AR4 SyR-SPM

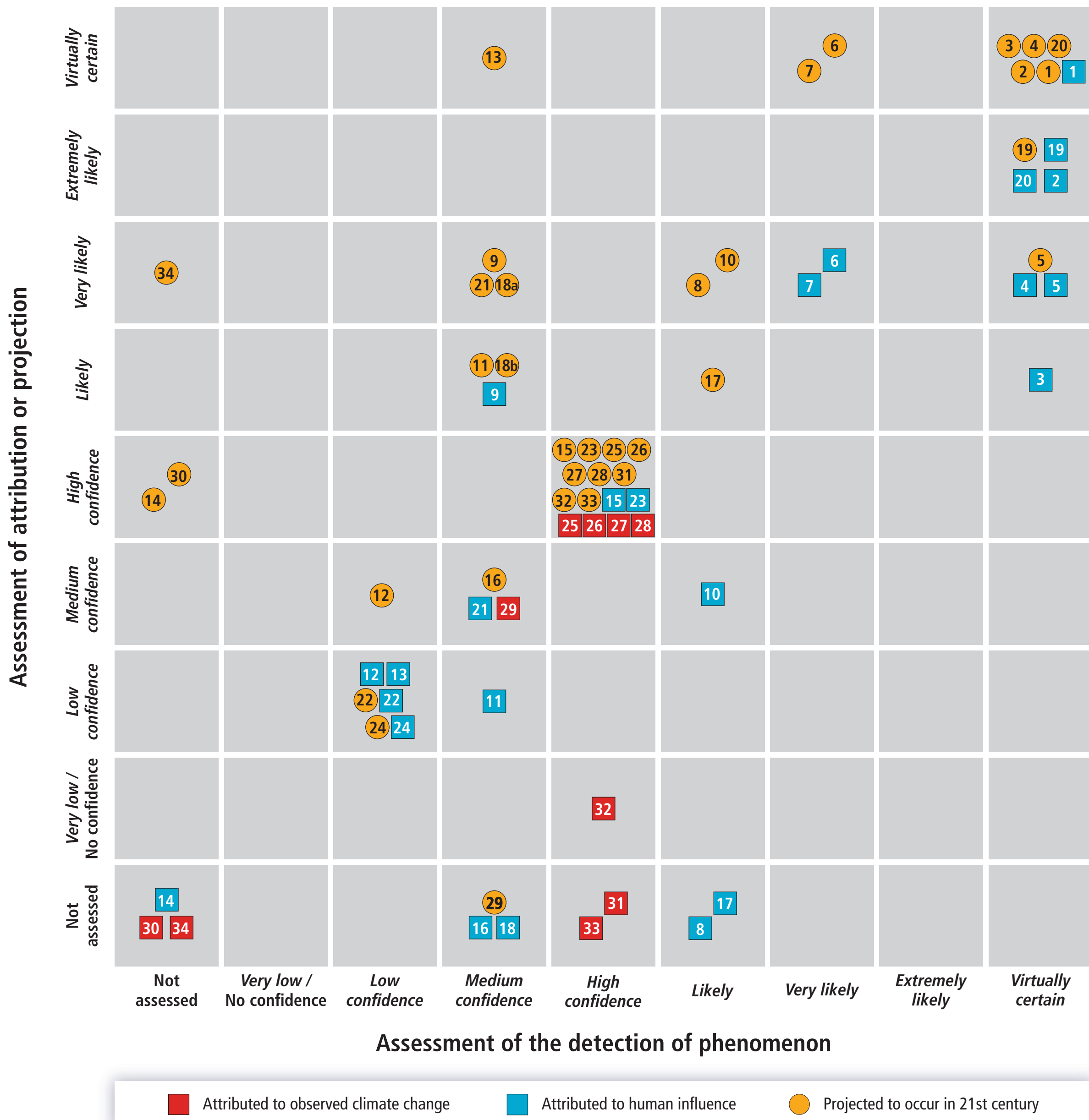


Figure 1-6 | Confidence in the attributed (squares) and projected 21st century (yellow circles) changes in climate system phenomena plotted as a function of confidence in their detection to date. Phenomena and sources (AR4, SREX, WGI AR5) are given in Table 1-2. Strength of confidence is sorted into the nine bins as noted on the axes (no assessment was made; a statement was made and assigned no formal confidence level or *very low confidence*; *low confidence*; *medium confidence; high confidence* (no quantification); or *likely; very likely; extremely likely; virtually certain*). Attribution is to either human influence (blue squares, as used by WGI) or observed local/regional climate change (red squares, as used by WGII). Projections assume global warming exceeding 2°C. For AR5 WGII results see, *inter alia*, Chapters 18 and 19.

attribution, or projection has been made across the Working Groups. A schematic presentation of this detection–attribution–projection sequence from preceding reports is given in Figure 1-6. For WGII AR5 attributions, see Chapter 18; and for projections, see the other chapters.

1.3.1. Special Report on Renewable Energy Sources and Climate Change Mitigation

SRREN (IPCC, 2011) assesses literature on the challenges of integrating renewable energy sources into existing energy sources to meet the goals of climate change mitigation and sustainable development. More specifically, it examines six renewable energy sources (bioenergy, direct solar energy, geothermal energy, hydropower, ocean energy, and wind energy) in terms of available technologies, technological potential, and associated costs. SRREN found that the deployment of renewable energy technologies has increased rapidly in recent years, often associated with cost reductions that are expected to continue with advancing technology. Despite the small contribution of renewable energy to current energy supplies, SRREN shows the global potential of renewable energy to be substantially higher than the global energy demand. It is therefore not the technological potential of renewable energy that constrains its development, but rather economic factors, system integration, infrastructure constraints, public acceptance, and sustainability concerns

Table 1-3 | Examples of linkages between the Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) and the AR5 WGII with chapter references in parentheses.

	SRREN findings	WGII AR5 findings
Water resources	Water availability limits the development of water cooled thermal power and hydropower. Environmental issues will continue to affect hydropower opportunities. (5.1, 5.6, 9.3)	Climate change is predicted to affect surface and groundwater supplies. Development of water-dependent energy resources can also affect freshwater ecosystems. (4.4, 19.3)
Ocean systems	Most ocean energy technologies are at the conceptual phase. Potential technologies include submarine turbines for tidal currents, ocean thermal energy conversion, and devices that harness energy of waves and salinity gradients. (6.2, 6.3, 6.5)	Offshore renewable energy introduces additional drivers of change for near- and offshore coastal and marine ecosystems and species. Ocean geoengineering approaches may have large environmental footprints. (5.5, 6.4)
Land cover changes	The sustainability of bioenergy (i.e., lifecycle GHG emissions) is influenced by land and biomass resource management practices. (2.2, 2,8, 9.3)	Land cover change associated with biofuel production has food security implications; related land use change can alter ecosystems, species, and carbon storage. (19.3, 19.4, 27.2)
Resilient pathways	Higher energy prices associated with transitions from fossil fuels to biofuels and other renewable energy sources may have adverse effects on socioeconomic development. (9.4, 10.5)	The challenge is to identify and implement mixes of technological options that reduce net carbon emissions and support sustained economic and social growth. (20.3)
Regional effects	Latin America is second to Africa for technical potential in producing bioenergy from rain-fed lignocellulosic feedstocks on unprotected grassland and woodlands. (2.2)	Bioenergy production requires large areas with risk of environmental degradation and may involve strong economic teleconnections (e.g., Latin America). (27.2, 27.3)
	The quantity of water resources availability in Central and South America is the largest in the world. The region has the largest proportion of electricity generated through hydropower facilities. (5.2)	Hydropower, the main source of renewable energy available in Central and South America, is prone to serious effects of climate change. Altered river flows affect development in this region and use of land for biofuel production. (27.3, 27.6, 27.8)

(IPCC, 2011). Several SRREN findings have clear linkages with this assessment of climate change impacts, adaptation, and vulnerability, as summarized in Table 1-3.

1.3.2. Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

SREX (IPCC, 2012) is the first IPCC Special Report produced jointly by Working Groups I and II and is the first IPCC report focused specifically on risk management. The report integrates perspectives from historically distinct research communities studying climate science, climate impacts, extreme events and impacts, climate adaptation, and disaster risk management. It assesses relationships between climate change and the characteristics of extreme weather and climate events. SREX provides information on existing societal exposure and vulnerability to climate-related extreme events and disasters; observed trends in weather- and climate-related disasters, disaster losses, and in disaster risk management; projected changes in weather and climate extremes during the 21st century; approaches for managing the increasing risks of climate extremes and disasters; and implications for sustainable development. SREX Chapter 9 is devoted to 14 case studies that illustrate the impacts of extreme climate-related events and options for risk management and adaptation, such as early-warning systems, new forms of insurance coverage, and expansion of social safety nets.

1.3.2.1. Themes and Findings of Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

The most relevant results of the SREX assessment follow. They are synthesized along these major themes: changing weather and climate-related extreme events, trends in disaster losses, and managing the risks of extreme events and disasters. Other examples of findings presented in SREX concerning the type, magnitude, and frequency of extreme weather and climate events are presented in Table 1-2 of this chapter.

- Based on observations since 1950 there is evidence of changes in some climate-related extremes. It is *very likely* that there has been an overall decrease in the number of cold days and nights, and increase in the number of warm days and nights, at the global scale (SREX SPM, Section 3.3.1, Table 3-2). It is *likely* that there has been an increase in extreme coastal high water events related to increases in mean sea level (SREX SPM, 3.5.3). It is *likely* that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale (SREX SPM, Sections 3.2.2, 3.3.1, 3.3.2, 3.4.4, 3.5.3, Table 3-1).
- The models project substantial warming in temperature extremes by the end of the 21st century. It is *virtually certain* that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century at the global scale. It is *very likely* that the length, frequency, and/or intensity of warm spells or heat waves will increase over most land areas (SREX SPM, Sections 3.3.2, 3.3.4, Table 3-3, Figure 3-5).
- It is *likely* that the frequency of heavy precipitation will increase in the 21st century over many areas of the globe (SREX SPM, Sections 3.3.2, 3.4.4, Table 3-3, Figure 3-7).
- Economic losses from weather- and climate-related disasters have increased, but with large spatial and interannual variability (*high confidence*, based on *high agreement*, *medium evidence*) (SREX SPM, Sections 4.5.1, 4.5.3, 4.5.4). Trends in losses have been heavily influenced by increasing exposure of people and economic assets (*high confidence*) (SREX SPM, Section 4.5.3).
- Economic, including insured, disaster losses associated with weather, climate-related events, and geophysical events are higher in developed countries. Fatality rates and economic losses expressed as a proportion of GDP are higher in developing countries (*high confidence*). Deaths from natural disasters occur much more in developing countries. From 1970 to 2008, for example, more than 95% of deaths from natural disasters were in developing countries (SREX SPM, Sections 4.5.2, 4.5.4).
- Development practice, policy, and outcomes contribute to shaping disaster risks (*high confidence*): skewed development that may lead to environmental degradation, unplanned urbanization, failure of governance, or reduction of livelihood options result in increased

exposure and vulnerability to disasters (SREX SPM, Sections 1.1.2, 1.1.3, 2.2.2, 2.5).

- Post-disaster recovery and reconstruction provide an opportunity for reducing the risks posed by future weather- and climate-related disasters (*robust evidence*, *high agreement*) (SREX SPM, Sections 5.2.3, 8.4.1, 8.5.2).
- Socioeconomic, demographic, health-related differences, access to livelihoods, good governance, and entitlements are some of the factors that lead to inequalities between people and countries. Inequalities influence local coping and adaptive capacity and pose challenges for risk management systems from local to national levels (*high agreement*, *robust evidence*) (SREX SPM, Sections 5.5.1, 6.2, 6.3.2, 6.6).
- The incorporation of climate change adaptation and disaster risk management into local, national, and international development practices and policies could bring benefits (*medium evidence*, *high agreement*) (SREX SPM, Sections 5.4, 5.5, 5.6, 6.3.1, 6.3.2, 6.4.2, 6.6, 7.4).
- Combining local knowledge with scientific and technical expertise helps communities reduce their risk and adapt to climate change (*robust evidence*, *high agreement*). Risk management works best when tailored to local circumstances (SREX SPM, Section 5.4.4).
- Many measures for managing current and future risks have additional benefits, such as improving peoples' livelihoods, conserving biodiversity, and improving human well-being (*medium evidence*, *high agreement*) (SREX SPM, Section 6.3.1, Table 6-1).
- Many measures, when implemented effectively, make sense under a range of future climates. These "low regrets" measures include systems that warn people of impending disasters; changes in land use planning; sustainable land management; ecosystem management; improvements in health surveillance, water supplies, and drainage systems; development and enforcement of building codes; and better education and awareness (SREX SPM, Sections 5.3,1, 5.3.4.3, 6.3.1, 6.5.1, 6.5.2, 7.4.3, Case Studies 9.2.11, 9.2.14).
- An iterative process involving monitoring, research, evaluation, learning, and innovation can promote adaptive management and reduce disaster risk in the context of climate extremes (*robust evidence*, *high agreement*) (SREX SPM, Sections 8.6.3, 8.7).
- Actions ranging from incremental improvements in governance and technology to more transformational changes are essential for reducing risk from climate extremes (*robust evidence*, *high agreement*) (SREX SPM, Sections 8.6, 8.6.3, 8.7).

1.3.2.2. Advances in Conceptualizing Climate Change Vulnerability, Adaptation, and Risk Management in the Context of Human Development

SREX conceptual framing reflects the diversity of expert communities involved in the assessment. It links exposure and vulnerability with socioeconomic development pathways as determinants of impacts and disaster risk for both human society and natural ecosystems. It is important to note that SREX acknowledges the fundamental role that values and aspirations play in people's perception of risk, of change and causality, and of imagining present and future situations. This value-based approach is put to work as a tool for managing the risks of extreme events and disasters enabling the recognition that socioeconomic systems are in constant flux, and that there are many conflicting and contradictory values in play. The conceptual framing of the problem space offered by SREX (SREX Figure SPM 1-1) serves as a point of departure for many WGII AR5 chapters. Equally important is the conceptualization of a feasible solution space offered in SREX. The solution space is further refined in the WGII AR5 through emphasis on co-benefits of adaptation and mitigation and the further development of transformational change to enable climate resilient development.

1.3.3. Relevant Findings from IPCC Working Group I Fifth Assessment Report

This section is a WGII synthesis of the WGI AR5 report that focuses on topics relevant to WGII science.[5] The relevant WGI AR5 chapters and sections are denoted in parentheses. Where statements have *high confidence* or *likely* or better quantification, these qualifiers are dropped for readability. Likewise, many phrases are exact quotations but are not presented in quotes. An overall assessment of climate change over the last several decades from WGI is: Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. Human influence on the climate system is clear; it has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes (SPM).

Greenhouse gases and climate forcing. Human activities are the dominant cause of the observed increase in well mixed GHGs since 1750 and of the consequent increase in climate forcing. The GHGs and their forcing continued to increase since AR4 (2, 6, 8). Ozone and stratospheric water vapor also contribute to this forcing (8). Aerosols partially offset this forcing and dominate the uncertainty in determining total anthropogenic forcing of climate change (8). Total anthropogenic climate forcing is positive and has increased more rapidly since 1970 than during prior decades (8). Present-day (2011) abundances of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) exceed the range over the past 800,000 years found in ice cores (5, 6). Annual emission of CO_2 from fossil fuels and cement production was 9.5 GtC in 2011, 54% above the 1990 level (SPM). More than 20% of added CO_2 will remain in the atmosphere for longer than 1000 years (6). Anthropogenic land use change has increased the land surface albedo (a negative forcing) and has also affected climate through the hydrologic cycle, but these effects

[5] This narrative is taken primarily from the executive summaries of the WGI Final Draft chapters and reflects the WGI SPM approved on 27 September 2013 in Stockholm. For the most part, WGI findings summarized here have *high confidence* or a *likely* or better quantification, and hence the confidence and likelihood statements have been dropped for readability. All quantitative ranges are *likely* (66% confidence) or *very likely* (90% confidence) or the modeled range (where noted). In a few instances, assessments with *low confidence* are included and so noted. This WGII narrative is intended to be accurate, but for the purpose here the exact WGI language has been edited and concatenated where possible (e.g., 1950 is substituted for "the middle of the 20th century"). Although quotation marks are not used, there remain long phrases that are direct quotes from the WGI AR5 chapters. All numerical values are verbatim. For the level of uncertainty and the precise wording of the WGI assessment refer directly to the WGI approved SPM and the accepted chapters.

are more uncertain and difficult to quantify (8.3.5). Spatial gradients in forcing (i.e., aerosols, ozone, land use change) affect regional temperature responses (8). Cumulative CO_2 emissions from 1750 to 2011 are 365 GtC (fossil fuel and cement) plus 180 GtC (deforestation and other land use change) (SPM). This 545 GtC represents about half of the 1000 GtC total that can be emitted and still keep global warming under 2°C relative to the reference period 1861–1880 (SPM).

Air quality on continental scales. Future surface ozone (air pollution) decreases over most continents for RCP2.6, RCP4.5, and RCP6.0; but it increases for RCP8.5 due to rising CH_4 (11). Changes in air quality for the RCPs are driven primarily by pollutant emissions and secondarily by climate change (11). Air pollution is less under RCP scenarios than under SRES scenarios (11).

Surface Temperatures. Global mean surface temperature increased by 0.85°C (0.65°C to 1.06°C) over the period 1880–2012 (linear trend) (SPM) and by 0.72°C over the period 1951–2012 (2). Each of the last 3 decades (from 1983 to 2012) has been successively warmer than any preceding decade since 1850 (SPM). The decade 2003–2012 has been the warmest over the instrumental record, even though the rate of warming over 1998–2012 is smaller than the average rate since 1951 (0.05°C vs. 0.12°C per decade) (2). For the NH, the period 1983–2012 was the warmest of the last 1.400 kyr (5). The slower surface warming trend over the period 1998–2012 vs. 1951–2012 is due in roughly equal measure to a reduced trend in radiative forcing and a cooling contribution from internal, possibly oceanic variability (SPM). Models reproduce the overall 1951–2012 warming trend, but not the smaller trend for 1998–2012 (9). More than half of the 1951–2010 temperature increase is due to the observed anthropogenic increase in GHGs (10). The projected near term (2016–2035) mean surface temperature increase is 0.9°C to 1.3°C (11), and the long term (2081–2100) ranges from 0.9°C to 2.3°C (RCP2.6) to 3.2°C to 5.4°C (RCP8.5) (values are relative to 1850–1900, the earliest period for which global mean surface temperatures have been measured, and include the 0.6°C offset from that period to the model reference period 1986–2005) (SPM, 2, 12).

Global temperatures during the last interglacial period (about 120,000 years ago) were never more than 2°C higher than preindustrial levels (5). By 2050 the global warming range is 1.5°C to 2.3°C above the 1850–1900 period based on the range across all RCPs and models (11.3.6). Near the end of the century (2081–2100) warming above 4°C is typical of RCP8.5, while that of RCP2.6 remains below 2°C (12). Orbital forcing will not trigger widespread glaciation during the next 1000 years (5).

Climate models reproduce observed continental-scale mean surface temperature patterns; on sub-continental and smaller scales model capability is reduced, but is better than in AR4 (9). Regional downscaling provides climate information at the smaller scales needed for impact studies and adds value in regions with highly variable topography and for various small-scale phenomena (9). Anthropogenic warming in the 21st century will proceed more rapidly over land areas than over oceans, and the Arctic region is projected to warm the most (11, 12).

Precipitation. Observed trends in global land-average precipitation have *low confidence* prior to 1950 and *medium confidence* thereafter (2). Simulation of large-scale precipitation patterns has improved somewhat since AR4, but precipitation at regional scales is not well simulated (9). Precipitation (global annual averages) will increase as temperatures increase, and the contrast between dry and wet regions and that between wet and dry seasons will increase over most of the globe (12). By 2100 under RCP8.5, high latitudes will experience more precipitation; many moist mid latitude regions will also experience more; while many mid-latitude and subtropical arid and semi-arid regions will experience less (12). These patterns are also typical of near-term climate change (11). Trends will not be apparent in all regions, especially in the near term, because of natural variability and possible influences of aerosols and land use change (11).

Extreme temperatures and precipitation. Since 1950, the numbers of cold days/nights have decreased and the numbers of warm days/nights have increased globally (2); and model simulation of these extreme events has improved since AR4 (9). Since 1950, anthropogenic forcing has contributed to the observed changes in daily temperature extremes on the global scale (10). In most regions the frequency of warm days/nights will increase in the next decades, while that of cold days/nights will decrease (11). Increases in the frequency, duration, and magnitude of hot extremes along with heat stress are expected; however, occasional cold winter extremes will occur (12). Extreme high temperatures (20-year return values) are projected to increase at a rate similar to or greater than the rate of increase of summer mean temperatures in most regions (12). There is a *no confidence* level assigned to projected near-term increases in the duration, intensity, and spatial extent of heat waves and warm spells (11), but in the long term heat waves will occur at higher frequency and longer duration in response to increased seasonal mean temperatures (12.4.3). Since 1950, the frequency or intensity of heavy precipitation events has increased in North America and Europe (2, SPM). Trends in small-scale severe weather events (e.g., hail, thunderstorms) have *low confidence* (2). With global warming, the frequency and intensity of heavy/extreme precipitation events will increase over most mid-latitude land and over wet tropical regions (12), and extreme daily precipitation rates will increase faster than the mean time average (7). Most models underestimate the sensitivity of extreme precipitation to temperature variability/trends, and thus projections may underestimate these extremes (9).

Floods and droughts. In many regions, historical droughts (last 1000 years) and historical floods (last 500 years) have been more severe than those observed since 1900 (5). Global-scale trends in drought or dryness since 1950 have *low confidence* due to lack of direct observations, methodological uncertainties, and geographical inconsistencies; hence confidence levels in global drought trends since the 1970s as reported in AR4 are overstated (2). Regional trends are found: the frequency and intensity of drought has increased in the Mediterranean and West Africa, and it has decreased in central North America and northwest Australia since 1950 (2, 2.6.2.2). There is *low confidence* in attributing drought changes to human influence (10). Projected changes in soil moisture and surface runoff have low confidence in the near term (11), but by 2100 under RCP8.5, annual runoff will decrease in parts of southern Europe, Middle East, and southern Africa, and increase in high northern latitudes (12). Decreases in soil moisture with increased risk of agricultural drought are projected in presently dry regions (12).

Tropical cyclones, storms, and wave heights. Observed changes in tropical cyclone activity on a centennial scale as well as attribution to human influence have *low confidence* (2, 10); however, the frequency and intensity of the strongest tropical cyclones in the North Atlantic have increased since the 1970s (2). In a few studies, high-resolution atmospheric models have reproduced the year-to-year variability of Atlantic hurricane counts (9). Future changes in intensity and frequency of tropical cyclones will vary by region, but basin-specific projections have *low confidence* (11, 14). The maximum wind speed and precipitation rates of tropical cyclones will increase (14).

Atmospheric circulation features have moved poleward since the 1970s, including a poleward shift of storm tracks and jet streams (2), and model simulation of these patterns has improved since AR4 (9). Large-scale trends in storminess over the last century have *low confidence* (2, 2.6.4). Projections of the position and strength of NH storm tracks, especially for the North Atlantic basin, have *low confidence* (11, 12, 14). With global warming, a shift to more intense individual storms and fewer weak storms is projected (12).

Mean significant wave height has increased over much of the Atlantic Ocean north of 45°N since 1950, with winter season trends of up to 20 cm per decade (*medium confidence*) (3, 3.4.5). Wave heights and the duration of the wave season will increase in the Arctic Ocean as a result of reduced sea ice extent (13). Wave heights will increase in the Southern Ocean as a result of enhanced wind speeds (13).

Ocean warming, stratification, and circulation. Overall, the ocean has warmed throughout most of its depth over some periods since 1950, and this warming accounts for about 93% of the increase in the Earth's energy inventory between 1971 and 2010 (3). The upper ocean above 700 m has warmed from 1971 to 2010, and the thermal stratification has increased by about 4% above 200 m depth (3). Anthropogenic forcings have made a substantial contribution this upper ocean warming (10). Measurement errors in the temperature data sets have been corrected since the AR4 (10). The global ocean continues to warm in all RCP scenarios (11, 12). To date there is no observational evidence of a long-term trend in Atlantic Meridional Overturning Circulation (3); and over the 21st century it is projected to weaken but not undergo an abrupt transition or collapse (12).

Ocean acidification and low oxygen. Oceanic uptake of anthropogenic CO_2 results in gradual acidification of the ocean (3). Since 1750 the pH of seawater has decreased by 0.1 (a 26% increase in hydrogen ion concentration) (3). Increased storage of carbon by the oceans over the 21st century will increase acidification, decreasing pH further by 0.065 for RCP2.6 and 0.31 for RCP8.5 (6). Aragonite under-saturation becomes widespread in parts of the Arctic and Southern Oceans and in some coastal upwelling systems at atmospheric CO_2 levels of 500 to 600 ppm (6). Oxygen concentrations have decreased since the 1960s in the open ocean thermocline of many regions (*medium confidence*) (3). By 2100, the oxygen content of the ocean will decrease by a few percent (6). There is no consensus on projection of the very low oxygen (hypoxic or suboxic) waters in the open ocean (6).

Sea ice. Continuing the trends reported in AR4, the annual Arctic sea ice extent decreased at rate of 3.5 to 4.1% per decade between 1979 and 2012 (4). Over the past 3 decades, Arctic summer sea ice retreat was unprecedented and Arctic sea surface temperatures were anomalously high, compared with the last 1450 years (SPM). The Arctic average winter sea ice thickness decreased between 1980 and 2008 (4). Current climate models reproduce the seasonal cycle and downward trend of Arctic sea ice extent (9). Anthropogenic forcings have contributed to Arctic sea ice loss since 1979 (10). With global warming, further shrinking and thinning of Arctic sea ice cover is projected, and the Arctic Ocean will be nearly ice free in September before 2050 for the high-warming scenarios like RCP8.5 (11, 12). There is little evidence in climate models of an Arctic Ocean tipping point, that is, the transition from a perennially ice covered to a seasonally ice-free expanse beyond which further sea ice loss is unstoppable and irreversible (12). Annual Antarctic sea ice extent increased by 1.2 to 1.8% per decade between 1979 and 2012 (4). The scientific understanding of this observed increase has *low confidence* (10). With global warming, Antarctic sea ice extent and volume is expected to decrease (*low confidence*) (12).

Ice sheets, glaciers, snow cover, and permafrost. During periods over the past few million years that were globally warmer than present, the Greenland and West Antarctic ice sheets were smaller (5). The Antarctic and Greenland ice sheets have on average lost ice during the last 2 decades, and the rate of loss has increased over the most recent decade to a sea level rise equivalent of 0.6 mm yr^{-1} for Greenland and 0.4 mm yr^{-1} for Antarctica (4). Anthropogenic influences have contributed to Greenland ice loss since 1990 and to the retreat of glaciers since the 1960s, but there is *low confidence* in attributing the causes of Antarctic ice loss (10). With global warming, model studies agree that the Greenland ice sheet will significantly decrease in area and volume, while the Antarctic ice sheet increases in most projections (*confidence* not assessed) (12, 13.4.4). Global warming above a certain threshold (e.g., 2°C to 4°C above the 1850–1900 period) would lead to the near-complete loss of the Greenland Ice Sheet over a millennium or more (*confidence* not assessed) (13). There is *low confidence* and little consensus on the likelihood of abrupt or nonlinear changes in components of the climate system over the 21st century (12).

Multiple lines of evidence support very substantial Arctic warming since the mid-20th century (SPM). Almost all glaciers world-wide have continued to shrink since AR4 (4). Over the last decade, most ice was lost from glaciers in the Canadian Arctic, Greenland ice sheet periphery, Southern Andes, Asian Mountains, and Alaska (4). Current glacier extents are out of balance with current climate, and glaciers will continue to shrink even without further warming (4). Snow cover extent has decreased in the NH, particularly in spring (4); and reductions since 1970 have an anthropogenic component (10). Permafrost temperatures have increased in most regions since the early 1980s: observed warming was up to 3°C in parts of Northern Alaska and 2°C in parts of the Russian European North (4, SPM). With global warming, NH snow cover extent and permafrost extent will decrease further (11, 12). By 2100 the decrease in near-surface permafrost area ranges from 37% (RCP2.6) to 81% (RCP8.5) (*medium confidence*) (12).

Sea level rise. During the last interglacial period, when global mean temperatures were no more than 2°C above pre-industrial values (*medium confidence*), maximum global mean sea level was, for several thousand years, 5 m to 10 m higher than present (SPM, 5, 5.3.4, 5.6.1, 5.6.2, 13, 13.2.1) with substantial contributions from Greenland and Antarctic Ice Sheets (5, 13). The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous 2 millennia (SPM). Global mean sea level has risen at an average rate of 1.7 mm yr^{-1} from 1901 to 2010 and at a faster rate, 3.2 mm yr^{-1}, from 1993 to 2010 (3). There is a substantial anthropogenic contribution to the global mean sea level rise since the 1970s (10). The rate of global mean sea level rise during the 21st century will exceed that observed during 1971–2010 for all RCP scenarios (13). For the period 2081–2100 compared to 1986–2005, process-based models project a global mean sea level rise ranging from 0.26 to 0.55 m (RCP2.6) up to 0.45 to 0.82 m (RCP8.5) (13). By 2100 for RCP8.5, this rise is 0.52 to 0.98 m, with a rate of rise reaching 8 to 16 mm yr^{-1} (SPM, 13). Only collapse of marine-based sectors of the Antarctic ice sheet could cause global mean sea level to rise substantially above these projections, probably not exceeding several tenths of a meter (*medium confidence*) by 2100 (13). Semi-empirical projections of 2100 sea level rise have a wide spread across models, some overlapping with the process-based models and some twice as large; however, there is *low confidence* in these projections (13, 13.5.2, 13.5.3). If global warming exceeds a certain threshold resulting in near-complete loss of the Greenland Ice Sheet over a millennium or more (*confidence* not assessed), global mean sea level would rise about 7 m (13). Future sea level change will vary regionally, but about 70% of the global coastlines are projected to experience a sea level change within 20% of the global mean (13).

The magnitude of extreme high sea level events has increased since 1970 (3). Future sea level extremes will become more frequent beyond 2050, primarily as a result of increasing mean sea level (13). By 2100 the frequency of current sea level extremes will increase by large factors in some regions (13, 13.7.2). Region-specific projections of storminess and associated storm surges have low confidence (13).

Climate patterns. The El Niño-Southern Oscillation (ENSO) system has remained highly variable throughout the past 7000 years with no discernible evidence of orbital modulation (5). The observed variability of the ENSO in the tropical Pacific is now reproduced in most climate models (9). Models project an eastward shift in the ENSO teleconnection patterns of temperature and precipitation variations over the North Pacific and North America (14). ENSO remains the dominant mode of interannual climate variability in the future, and the ENSO precipitation anomalies will intensify due to increased moisture (14). Aggregated over all monsoon systems and over the 21st century, the monsoon will increase in area and intensity while its circulation weakens (14). Monsoon onset dates become earlier or do not change and monsoon retreat dates delay, lengthening the monsoon season (14). Reduced warming and decreased precipitation is projected in the eastern tropical Indian Ocean, with increased warming and precipitation in the western, influencing East Africa and Southeast Asia precipitation (14).

1.3.4. Relevant Findings from IPCC Working Group III Fifth Assessment Report

The WGIII report assesses scientific research related to the mitigation of climate change. Because mitigation lowers the effects of climate change as well as the risks of extreme impacts, it is part of a broader policy strategy that includes adaptation to climate impacts. Both mitigation (WGIII) and adaptation (WGII) involve risk management in the context of many prevailing uncertainties. Uncertainties arise not only in the natural but also in human and social systems, including responses of these to policy interventions. It is possible that extreme climate impacts could play a central role in determining the level of mitigation, adaptation, and other policy responses to climate change (WGIII AR5 Chapter 2).

Over the last two WGIII assessment reports, one of the most important shifts in the scientific literature reflects underlying changes in the structure of the world economy: the underlying determinants of emissions—such as technologies, investment patterns, resource use, lifestyles, and development pathways in general—have not substantially shifted toward a low-GHG pattern despite the adoption of the UNFCCC and the Kyoto Protocol. In 2010, GHG emissions surpassed 50 Gt CO_2-eq (13.6 GtC), higher than in any previous year since 1750. Most of the emission growth between 2000 and 2010 came from fossil-fuel use in the energy and industry sectors, and took place in emerging economies. This emission growth was not met by significant GHG emission cuts in the industrialized country group, which continued to dominate historical long-term contributions to global CO_2 emissions. In 2010, median per capita GHG emissions in high-income countries were roughly 10 times higher than in low-income countries (WGIII AR5 Chapters 1, 5).

One of the central messages of WGIII AR5 is that technological and behavioral options exist that would allow the world's economies to follow pathways to much lower future emissions of GHGs. Since AR4 a substantial scenario literature has emerged on the technological, economic, and institutional conditions needed to achieve different long-term pathways leading to a stabilization of atmospheric GHG concentrations in 2100. A continuation of current trends of technological change in the absence of explicit climate change mitigation policies is not sufficient to bring about stabilization of GHGs. Scenarios that are *more likely than not* to limit temperature increase to 2°C are becoming increasingly challenging, and most of these include a temporary overshoot of this concentration goal requiring net negative CO_2 emissions after 2050 and thus large-scale application of carbon dioxide removal (CDR) technologies (WGIII AR5 Chapter 6). CDR methods are not mature and have biogeochemical and technological limitations to their potential on a global scale and carry side effects and long-term consequences on a global scale (WGI AR5 SPM; WGIII AR5 Chapter 6). The increasing dependence of pathways on CDR options reduces the ability of policymakers to hedge risks freely across the mitigation technology portfolio (WGIII AR5 Chapter 6). The literature highlights the importance of a systemic, cross-sectoral approach to mitigation. Approaches that emphasize only a subset of sectors or a subset of actions may miss synergies between sectors, raise the costs of mitigation, cause unexpected consequences, and prove insufficient to meet long-term mitigation goals (WGIII AR5 Chapters 6 to 11). The costs of mitigation grow over-proportionally with the stringency of the stabilization target. Delays in mitigation and the unavailability of individual mitigation technologies increase the cost of mitigation and negatively affect the probability of meeting ambitious long-term atmospheric stabilization goals (WGIII AR5 Chapter 6).

Mitigation policies involve multiple actors and institutions at the international, regional, national, and sub-national scales—from global treaties to firms and individual households. Since AR4 a body of literature has been emerging to explain how this multiplicity of actors and levels, focused on a multiplicity of interacting goals, affects the design and evolution of mitigation policy (WGIII AR5 Chapters 13, 14, 15). Approaches to international cooperation in climate policies have increased and become more diverse ranging from strong multi-lateralism to harmonized national and regional policies (WGIII AR5 Chapter 13). Linkages among regional, national, and sub-national programs may complement international cooperation. Carbon markets have been the focus of regional policy due, in part, to the greater opportunities for trade as carbon markets expand (WGIII AR5 Chapters 13, 14). A combination of policies that address providing a price signal, removing barriers, and promoting long-term investments could be most effective. If there is no coordination within an integrated perspective then results in one area may be counteracted by results in another area, for instance through leakage and rebound effects (WGIII AR5 Chapter 15).

While mitigation efforts generate costs and trade-offs, they also offer possible synergies because many of the policies that can mitigate GHGs also help address other policy goals, such as managing air pollution, water scarcity, or energy security. Since AR4 a substantial literature has emerged on this topic, underscoring the link of mitigation to a wide range of societal goals, often designated as sustainable development (WGIII AR5 Chapters 3, 4, 15).

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2 Foundations for Decision Making

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Executive Summary

Decision support for impacts, adaptation, and vulnerability is expanding from science-driven linear methods to a wide range of methods drawing from many disciplines (*robust evidence*, *high agreement*). This chapter introduces new material from disciplines including behavioral science, ethics, and cultural and organizational theory, thus providing a broader perspective on climate change decision making. Previous assessment methods and policy advice have been framed by the assumption that better science will lead to better decisions. Extensive evidence from the decision sciences shows that while good scientific and technical information is necessary, it is not sufficient, and decisions require context-appropriate decision-support processes and tools (*robust evidence*, *high agreement*). There now exists a sufficiently rich set of available methods, tools, and processes to support effective climate impact, adaptation, and vulnerability (CIAV) decisions in a wide range of contexts (*medium evidence*, *medium agreement*), although they may not always be appropriately combined or readily accessible to decision makers. {2.1.1, 2.1.2, 2.1.3, 2.3}

Risk management provides a useful framework for most climate change decision making. Iterative risk management is most suitable in situations characterized by large uncertainties, long time frames, the potential for learning over time, and the influence of both climate as well as other socioeconomic and biophysical changes (*robust evidence*, *high agreement*). Complex decision-making contexts will ideally apply a broad definition of risk, address and manage relevant perceived risks, and assess the risks of a broad range of plausible future outcomes and alternative risk management actions (*robust evidence*, *medium agreement*). The resulting challenge is for people and organizations to apply CIAV decision-making processes in ways that address their specific aims. {2.1.2, 2.2.1, 2.3, 2.4.3}

Decision support is situated at the intersection of data provision, expert knowledge, and human decision making at a range of scales from the individual to the organization and institution. Decision support is defined as a set of processes intended to create the conditions for the production of decision-relevant information and its appropriate use. Such support is most effective when it is context-sensitive, taking account of the diversity of different types of decisions, decision processes, and constituencies (*robust evidence*, *high agreement*). Boundary organizations, including climate services, play an important role in climate change knowledge transfer and communication, including translation, engagement, and knowledge exchange (*medium evidence*, *high agreement*). {2.1.3, 2.2.1, 2.2, 2.3, 2.4.1, 2.4.2, 2.4.3}

Scenarios are a key tool for addressing uncertainty (*robust evidence*, *high agreement*). They can be divided into those that explore how futures may unfold under various drivers (problem exploration) and those that test how various interventions may play out (solution exploration). Historically, most scenarios used for CIAV assessments have been of the former type, though the latter are becoming more prevalent (*medium evidence*, *high agreement*). The new RCP scenario process can address both problem and solution framing in ways that previous IPCC scenarios have not been able to (*limited evidence*, *medium agreement*). {2.2.1.3, 2.3.2}

CIAV decision making involves ethical judgments expressed at a range of institutional scales; the resulting ethical judgements are a key part of risk governance (*robust evidence*, *medium agreement*). Recognition of local and indigenous knowledge and diverse stakeholder interests, values, and expectations is fundamental to building trust within decision-making processes (*robust evidence*, *high agreement*). {2.2.1.1, 2.2.1.2, 2.2.1.3, 2.2.1.4, 2.4, 2.4.1}

Climate services aim to make knowledge about climate accessible to a wide range of decision makers. In doing so they have to consider information supply, competing sources of knowledge, and user demand. Knowledge transfer is a negotiated process that takes a variety of cultural values, orientations, and alternative forms of knowledge into account (*medium evidence*, *high agreement*). {2.4.1, 2.4.2}

Climate change response can be linked with sustainable development through actions that enhance resilience, the capacity to change in order to maintain the same identity while also maintaining the capacity to adapt, learn, and transform. Mainstreamed adaptation, disaster risk management, and new types of governance and institutional arrangements are being studied for their potential to support the goal of enhanced resilience (*medium evidence*, *high agreement*). {2.5.2}

Transformational adaptation may be required if incremental adaptation proves insufficient (*medium evidence*, *high agreement*). This process may require changes in existing social structures, institutions, and values, which can be facilitated by iterative risk management and triple-loop learning that considers a situation and its drivers, along with the underlying frames and values that provide the situation context. {2.1.2, 2.5.3}

2.1. Introduction and Key Concepts

This chapter addresses the foundations of decision making with respect to climate impact, adaptation, and vulnerability (CIAV). The Fourth Assessment Report (AR4) summarized methods for assessing CIAV (Carter et al., 2007), which we build on by surveying the broader literature relevant for decision making.

Decision making under climate change has largely been modeled on the scientific understanding of the cause-and-effect process whereby increasing greenhouse gas emissions cause climate change, resulting in changing impacts and risks, potentially increasing vulnerability to those risks. The resulting decision-making guidance on impacts and adaptation follows a rational-linear process that identifies potential risks and then evaluates management responses (e.g., Carter et al., 1994; Feenstra et al., 1998; Parry and Carter, 1998; Fisher et al., 2007). This process has been challenged on the grounds that it does not adequately address the diverse contexts within which climate decisions are being made, often neglects existing decision-making processes, and overlooks many cultural and behavioral aspects of decision making (Smit and Wandel, 2006; Sarewitz and Pielke, 2007; Dovers, 2009; Beck, 2010). While more recent guidance on CIAV decision making typically accounts for sectoral, regional, and socioeconomic characteristics (Section 21.3), the broader decision-making literature is still not fully reflected in current methods. This is despite an increasing emphasis on the roles of societal impacts and responses to climate change in decision-making methodologies (*high confidence*) (Sections 1.1, 1.2, 21.2.1).

The main considerations that inform the decision-making contexts addressed here are knowledge generation and exchange, who makes and implements decisions, and the issues being addressed and how these can be addressed. These decisions occur within a broader social and cultural environment. Knowledge generation and exchange includes knowledge generation, development, brokering, exchange, and application to practice. Decision makers include policymakers, managers, planners, and practitioners, and range from individuals to organizations and institutions (Table 21-1). Relevant issues include all areas affected directly and indirectly by climate impacts or by responses to those impacts, covering diverse aspects of society and the environment. These issues include consideration of values, purpose, goals, available resources, the time over which actions are expected to remain effective, and the extent to which the objectives being pursued are regarded as appropriate. The purpose of the decision in question, for example, assessment, strategic planning, or implementation, will also define the framework and tools needed to enable the process. This chapter neither provides any standard template or instructions for decision making, nor does it endorse particular decisions over others.

The remainder of this chapter is organized as follows. Section 2.1.2 addresses risk management, which provides an overall framework suitable for CIAV decision making; Section 2.1.3 introduces decision support; Section 2.2 discusses contexts for decision making; Section 2.3 discusses methods, tools, and processes; Section 2.4 discusses support for and application of decision making; and Section 2.5 describes some of the broader contexts influencing CIAV decision making.

2.1.1. Decision-Making Approaches in this Report

The overarching theme of the chapter and the AR5 report is managing current and future climate risks (Sections 1.2.4, 16.2, 19.1), principally through adaptation (Chapters 14 to 17), but also through resilience and sustainable development informed by an understanding of both impacts and vulnerability (Section 19.2). The International Standard ISO:31000 defines risk as *the effect of uncertainty on objectives* (ISO, 2009) and the Working Group II AR5 Glossary defines risk as *The potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain* (Rosa, 2003). However, the Glossary also refers to a more operational definition for assessing climate-related hazards: *risk is often represented as probability of occurrence of hazardous events or trends multiplied by the consequences if these events occur.* Risk can also refer to an uncertain opportunity or benefit (see Section 2.2.1.3). This chapter takes a broader perspective than the latter by including risks associated with taking action (e.g., will this adaptation strategy be successful?) and the broader socially constructed risks that surround "climate change" (e.g., fatalism, hope, opportunity, and despair).

Because all decisions on CIAV are affected by uncertainty and focus on valued objectives, all can be considered as decisions involving risk (e.g., Giddens, 2009) (*high confidence*). AR4 endorsed iterative risk management as a suitable decision support framework for CIAV assessment because it offers formalized methods for addressing uncertainty, involving stakeholder participation, identifying potential policy responses, and evaluating those responses (Carter et al., 2007; IPCC, 2007b; Yohe et al., 2007). The literature shows significant advances on all these topics since AR4 (Section 1.1.4), greatly expanding methodologies for assessing impacts, adaptation, and vulnerability in a risk context (Agrawala and Fankhauser, 2008; Hinkel, 2011; Jones and Preston, 2011; Preston et al., 2011).

Many different risk methodologies, such as financial, natural disaster, infrastructure, environmental health, and human health, are relevant for CIAV decision making (*very high confidence*). Each methodology utilizes a variety of different tools and methods. For example, the standard CIAV methodology follows a top-down cause and effect pathway as outlined previously. Others follow a bottom-up pathway, starting with a set of decision-making goals that may be unrelated to climate and consider how climate may affect those goals (see also Sections 15.2.1, 15.3.1). Some methodologies such as vulnerability, resilience, and livelihood assessments are often considered as being different from traditional risk assessment, but may be seen as dealing with particular stages within a longer term iterative risk management process. For example, developing resilience can be seen as managing a range of potential risks that are largely unpredictable; and sustainable development aims to develop a social-ecological system robust to climate risks.

A major aim of decision making is to make good or better decisions. Good and better decisions with respect to climate adaptation are frequently mentioned in the literature but no universal criterion exists for a good decision, including a good climate-related decision (Moser and Ekstrom, 2010). This is reflected in the numerous framings linked to adaptation decision making, each having its advantages and disadvantages

Frequently Asked Questions

FAQ 2.1 | What constitutes a good (climate) decision?

No universal criterion exists for a good decision, including a good climate-related decision. Seemingly reasonable decisions can turn out badly, and seemingly unreasonable decisions can turn out well. However, findings from decision theory, risk governance, ethical reasoning, and related fields offer general principles that can help improve the quality of decisions made.

Good decisions tend to emerge from processes in which people are explicit about their goals; consider a range of alternative options for pursuing their goals; use the best available science to understand the potential consequences of their actions; carefully consider the trade-offs; contemplate the decision from a wide range of views and vantages, including those who are not represented but may be affected; and follow agreed-upon rules and norms that enhance the legitimacy of the process for all those concerned. A good decision will be implementable within constraints such as current systems and processes, resources, knowledge, and institutional frameworks. It will have a given lifetime over which it is expected to be effective, and a process to track its effectiveness. It will have defined and measurable criteria for success, in that monitoring and review is able to judge whether measures of success are being met, or whether those measures, or the decision itself, need to be revisited.

A good climate decision requires information on climate, its impacts, potential risks, and vulnerability to be integrated into an existing or proposed decision-making context. This may require a dialog between users and specialists to jointly ascertain how a specific task can best be undertaken within a given context with the current state of scientific knowledge. This dialog may be facilitated by individuals, often known as knowledge brokers or extension agents, and boundary organizations, who bridge the gap between research and practice. Climate services are boundary organizations that provide and facilitate knowledge about climate, climate change, and climate impacts for planning, decision making, and general societal understanding of the climate system.

(Preston et al., 2013; see also Section 15.2.1). Extensive evidence from the decision sciences shows that good scientific and technical information alone is rarely sufficient to result in better decisions (Bell and Lederman, 2003; Jasanoff, 2010; Pidgeon and Fischhoff, 2011) (*high confidence*). Aspects of decision making that distinguish climate change from most other contexts are the long time scales involved, the pervasive impacts and resulting risks, and the “deep” uncertainties attached to many of those risks (Kandlikar et al., 2005; Ogden and Innes, 2009; Lempert and McKay, 2011). These uncertainties include not only future climate but also socioeconomic change and potential changes in norms and values within and across generations.

2.1.2. Iterative Risk Management

Iterative risk management involves an ongoing process of assessment, action, reassessment, and response (Kambhu et al., 2007; IRGC, 2010) that will continue—in the case of many climate-related decisions—for decades if not longer (National Research Council, 2011). This development is consistent with an increasing focus on risk governance (Power, 2007; Renn, 2008), the integration of climate risks with other areas of risk management (Hellmuth et al., 2011; Measham et al., 2011), and a wide range of approaches for structured decision making involving process uncertainty (Ohlson et al., 2005; Wilson and McDaniels, 2007; Ogden and Innes, 2009; Martin et al., 2011).

Two levels of interaction can be recognized within the iterative risk management process: one internal and one external (Figure 2-1). External factors are present through the entire process and shape the process outcomes. The internal aspects describe the adaptation process itself. The first major internal iteration (in yellow) reflects the interplay with the analysis phase by addressing the interactions between evolving risks and their feedbacks (not shown) and during the development and choice of options. This process may also require a revision of criteria and objectives. This phase ends with decisions on the favored options being made. A further internal iteration covers the implementation of actions and their monitoring and review (in orange). Throughout all stages the process is reflexive, in order to enable changes in knowledge, risks, or circumstances to be identified and responded to. At the end of the implementation stage, all stages are evaluated and the process starts again with the scoping phase. Iterations can be successive, on a set timetable, triggered by specific criteria or informally by new information informing risk or a change in the policy environment. An important aspect of this process is to recognize emergent risks and respond to them (Sections 19.2.3, 19.2.4, 19.2.5, 19.3).

Complexity is an important attribute for framing and implementing decision-making processes (*very high confidence*). Simple, well-bounded contexts involving cause and effect can be addressed by straightforward linear methods. Complicated contexts require greater attention to process but can generally be unravelled, providing an ultimate solution (Figure 2-2). However, when complex environments interact with conflicting values they become associated with wicked problems. Wicked problems are not well bounded, are framed differently by various groups and individuals, harbor large scientific to existential uncertainties and have unclear solutions and pathways to those solutions (Rittel and Webber,

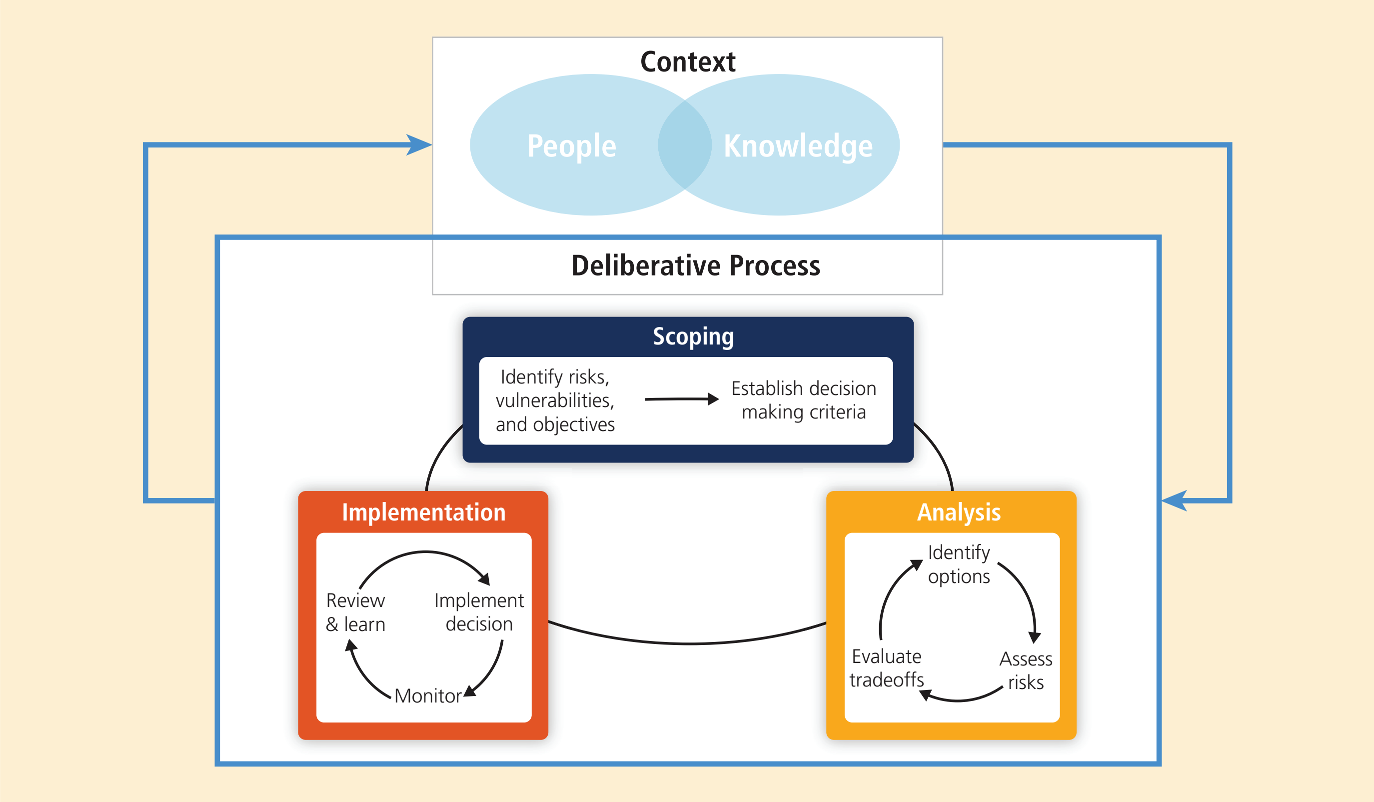


Figure 2-1 | Iterative risk management framework depicting the assessment process, and indicating multiple feedbacks within the system and extending to the overall context (adapted from Willows and Connell, 2003).

1973; Australian Public Service Commission, 2007). Such "deep uncertainty" cannot easily be quantified (Dupuy and Grinbaum, 2005; Kandlikar et al., 2005). Another important attribute of complex systems is *reflexivity*, where cause and effect feed back into each other (see Glossary). For example, actions taken to manage a risk will affect the outcomes, requiring iterative processes of decision making (*very high confidence*). Under climate change, calculated risks will also change with time as new knowledge becomes available (Ranger et al., 2010).

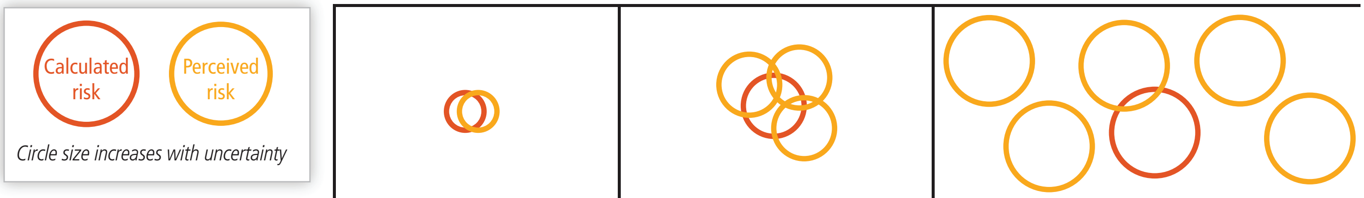
In complex situations, sociocultural and cognitive-behavioral contexts become central to decision making. This requires combining the scientific understanding of risk with how risks are framed and perceived by individuals, organizations, and institutions (Hansson, 2010). For that reason, formal risk assessment is moving from a largely technocratic exercise carried out by experts to a more participatory process of decision support (Fiorino, 1990; Pereira and Quintana, 2002; Renn, 2008), although this process is proceeding slowly (Christoplos et al., 2001; Pereira and Quintana, 2002; Bradbury, 2006; Mercer et al., 2008).

Different traditional and modern epistemologies, or "ways of knowing" exist for risk (Hansson, 2004; Althaus, 2005; Hansson, 2010), vulnerability (Weichselgartner, 2001; O'Brien et al., 2007), and adaptation assessments (Adger et al., 2009), affecting the way they are framed by various disciplines and are also understood by the public (Garvin, 2001; Adger, 2006; Burch and Robinson, 2007). These differences have been identified as a source of widespread misunderstanding and disagreement. They are also used to warn against a uniform epistemic approach (Hulme, 2009; Beck, 2010), a critique that has been leveled against previous IPCC assessments (e.g., Hulme and Mahony, 2010).

The following three types of risk have been identified as important epistemological constructs (Thompson, 1986; Althaus, 2005; Jones, 2012):

1. Idealized risk: the conceptual framing of the problem at hand. For example, dangerous anthropogenic interference with the climate system is how climate change risk is idealized within the UNFCCC.
2. Calculated risk: the product of a model based on a mixture of historical (observed) and theoretical information. Frequentist or recurrent risks often utilize historical information whereas single-event risks may be unprecedented, requiring a more theoretical approach.
3. Perceived risk: the subjective judgment people make about an idealized risk (see also Section 19.6.1.4).

These different types show risk to be partly an objective threat of harm and partly a product of social and cultural experience (Kasperson et al., 1988; Kasperson, 1992; Rosa, 2008). The aim of calculating risk is to be as objective as possible, but the subjective nature of idealized and perceived risk reflects the division between positivist (imposed norms) and constructivist (derived norms) approaches to risk from the natural and social sciences respectively (Demeritt, 2001; Hansson, 2010). Idealized risk is important for framing and conceptualizing risk and will often have formal and informal status in the assessment process, contributing to both calculated and perceived risk. These types of risk combine at the societal scale as socially constructed risk, described and



Characteristics of decision making	Simple risk	Complicated risk	Complex risk
Methodology	Linear, cause and effect	Top down and/or bottom up, iterative	Iterative and/or adaptive, ongoing and systemic
Approach	Analytic and technical	Collaborative process with technical input	Process driven. Frame and model multiple drivers and valued outcomes
Stakeholder strategy	Communication	Collaboration	Deliberation, creating shared understanding and ownership
Mental models	Common model	Negotiated and shared	Contested initially and negotiated over project
Values and outcomes	Widely accepted	Negotiated over project by user perspectives and calculated risk	Contested initially and negotiated over project
Monitoring	Straightforward	With review and trigger points	As real-time as possible, adaptive with management feedback and trigger points

Figure 2-2 | Hierarchy of simple, complicated, and complex risks, showing how perceived risks multiply and become less connected with calculated risk with increasing complexity. Also shown are major characteristics of assessment methods for each level of complexity.

assessed in a wide range of research literature such as psychology, anthropology, geography, ethics, sociology, and political science (see Sections 2.2.1.2, 19.6.1.4).

Acceptance of the science behind controversial risks is strongly influenced by social and cultural values and beliefs (Leiserowitz, 2006; Kahan et al., 2007; Brewer and Pease, 2008). Risk perceptions can be amplified socially where events pertaining to hazards interact with psychological, social, institutional, and cultural processes in ways that heighten or attenuate individual and social perceptions of risk and shape risk behavior (Kasperson et al., 1988; Renn et al., 1992; Pidgeon et al., 2003; Rosa, 2003; Renn, 2011). The media have an important role in propagating both calculated and perceived risk (Llasat et al., 2009), sometimes to detrimental effect (Boykoff and Boykoff, 2007; Oreskes and Conway, 2010; Woods et al., 2012).

Understanding how these perceptions resonate at an individual and collective level can help overcome constraints to action (Renn, 2011). Science is most suited to calculating risk in areas where it has predictive skill and will provide better estimates than may be obtained through more informal methods (Beck, 2000), but an assessment of what is at risk generally needs to be accepted by stakeholders (Eiser et al., 2012). Therefore, the science always sits within a broader social setting (Jasanoff, 1996; Demeritt, 2001; Wynne, 2002; Demeritt, 2006), often requiring a systems approach where science and policy are investigated in tandem, rather than separately (Pahl-Wostl, 2007; Ison, 2010) (*very high confidence*). These different types of risk give rise to complex interactions between formal and informal knowledge that cannot be bridged by better science or better predictions but require socially and culturally mediated processes of engagement (*high confidence*).

2.1.3. Decision Support

The concept of *decision support* provides a useful framework for understanding how risk-based concepts and information can help enhance decision making (McNie, 2007; National Research Council Panel on Design Issues for the NOAA Sectoral Applications Research Program et al., 2007; Moser, 2009; Romsdahl and Pyke, 2009; Kandlikar et al., 2011; Pidgeon and Fischhoff, 2011) The concept also helps situate methods, tools, and processes intended to improve decision making within appropriate institutional and cultural contexts.

Decision support is defined as "a set of processes intended to create the conditions for the production of decision-relevant information and for its appropriate use" (National Research Council, 2009a, p. 33). Information is decision-relevant if it yields deeper understanding of, or is incorporated into making a choice that improves outcomes for decision makers and stakeholder or precipitates action to manage known risks. Effective decision support provides users with information they find useful because they consider it credible, legitimate, actionable, and salient (e.g., Jones et al., 1999; Cash et al., 2003; Mitchell, 2006; Reid et al., 2007). Such criteria can be used to evaluate decision support and such evaluations lead to common principles of effective decision support, which have been summarized in National Research Council (2009b) as:

- Begins with user's needs, not scientific research priorities. Users may not always know their needs in advance, so user needs are often developed collaboratively and iteratively among users and researchers.
- Emphasizes processes over products. Though the information products are important, they are likely to be ineffective if they are not developed to support well-considered processes.

- Incorporates systems that link users and producers of information. These systems generally respect the differing cultures of decision makers and scientists, but provide processes and institutions that effectively link individuals from these differing communities.
- Builds connections across disciplines and organizations, in order to provide for the multidisciplinary character of the needed information and the differing communities and organizations in which this information resides.
- Seeks institutional stability, either through stable institutions and/or networks, which facilitates building the trust and familiarity needed for effective links and connections among information users and producers in many different organizations and communities.
- Incorporates learning, so that all parties recognize the need for and contribute to the implementation of decision support activities structured for flexibility, adaptability, and learning from experience.

These principles can lead to different decision support processes depending on the stage and context of the decision in question. For instance, decision support for a large water management agency operating an integrated system serving millions of people will have different needs than a small town seeking to manage its groundwater supplies. A community in the early stages of developing a response to climate change may be more focused on raising awareness of the issue among its constituents, while a community with a well-developed understanding of its risks may be more focused on assessing trade-offs and allocating resources.

2.2. Contexts for Decision Making

This section surveys aspects of decision making that relate to context setting. Social context addresses cultural values, psychology, language, and ethics (Section 2.2.1) and institutional context covers institutions and governance (Section 2.2.2).

2.2.1. Social Context

Decision support for CIAV must recognize that diverse values, language uses, ethics, and human psychological dimensions play a crucial role in the way that people use and process information and take decisions (Kahan and Braman, 2006; Leiserowitz, 2006). As illustrated in Figure 2-1, the context defines and frames the space in which decision-making processes operate.

2.2.1.1. Cultural Values and Determinants

Cultural differences allocate values and guide socially mediated change. Five value dimensions that show significant cross-national variations are: power distance, individualism/collectivism, uncertainty avoidance, long-/short-term orientation, and masculinity/femininity (Hofstede, 1980, 2001; Hofstede et al., 2010). Power distance and individualism/collectivism both show a link to climate via latitude; the former relates to willingness to conform to top-down directives, whereas the latter relates to the potential efficacy of market-/community-based strategies. Uncertainty avoidance and long-term orientation show considerable variation between countries (Hofstede et al., 2010), potentially producing significant differences in risk perception and agency.

Environmental values have also been linked to cultural orientation. Schultz et al. (2004) identified the association between self and nature in people as being implicit—informing actions without specific awareness. A strong association was linked to a more connected self and a weaker association with a more egoistic self. Explicit environmental values can substantially influence climate change-related decision-making processes (Nilsson et al., 2004; Milfont and Gouveia, 2006; Soyez et al., 2009) and public behavior toward policies (Stern and Dietz, 1994; Xiao and Dunlap, 2007). Schaffrin (2011) concludes that geographical aspects, vulnerability, and potential policy benefits associated with a given issue can influence individual perceptions and willingness to act (De Groot and Steg, 2007, 2008; Shwom et al., 2008; Milfont et al., 2010). Cultural values can interrelate with specific physical situations of climate change (Corraliza and Berenguer, 2000), or seasonal and meteorological factors influencing people's implicit connections with nature (Duffy and Verges, 2010). Religious and sacred values are also important (Goloubinoff, 1997; Katz et al., 2002; Lammel et al., 2008), informing the perception of climate change and risk, as well as the actions to adapt (Crate and Nuttal, 2009; see also Section 16.3.1.3). The role of protected values (values that people will not trade off, or negotiate) can also be culturally and spiritually significant (Baron and Spranca, 1997; Baron et al., 2009; Hagerman et al., 2010). Adger et al. (2013) emphasize the importance of cultural values in assessing risks and adaptation options, suggesting they are at least as important as economic values in many cases, if not more so. These aspects are important for framing and conceptualizing CIAV decision making. Cultural and social barriers are described in Section 16.3.2.7.

Two distinct ways of thinking—holistic and analytical thinking—reflect the relationship between humans and nature and are cross-culturally and even intra-culturally diverse (Gagnon Thompson and Barton, 1994; Huber and Pedersen, 1997; Atran et al., 2005; Ignatow, 2006; Descola, 2010; Ingold, 2011). Holistic thinking is primarily gained through experience and is dialectical, accepting contradictions and integrating multiple perspectives. Characteristic of collectivist societies, the holistic conceptual model considers that social obligations are reciprocal and individuals take an active part in the community for the benefit of all (Peng and Nisbett, 1999; Nisbett et al., 2001; Lammel and Kozakai, 2005; Nisbett and Miyamoto, 2005). Analytical thinking isolates the object from its broader context, understanding its characteristics through categorization, and predicting events based on intrinsic rules. In the analytic conceptual model, individual interests take precedence over the collective; the self is independent and communication comes from separate fields. These differences influence the understanding of complex systemic phenomena such as climate change (Lammel et al., 2011, 2012, 2013) and decision-making practices (Badke-Schaub and Strohschneider, 1998; Strohschneider and Güss, 1999; Güss et al., 2010).

The above models vary greatly across the cultural landscape, but neither model alone is sufficient for decision making in complex situations (*high confidence*). At a very basic level, egalitarian societies may respond more to community based adaptation in contrast to more individualistic societies that respond to market-based forces (*medium confidence*). In small-scale societies, knowledge about climate risks are often integrated into a holistic view of community and environment (e.g., Katz et al., 2002; Strauss and Orlove, 2003; Lammel et al., 2008). Many studies highlight the importance of integrating local, traditional knowledge with scientific knowledge when assessing CIAV (Magistro and Roncoli, 2001; Krupnik and Jolly, 2002; Vedwan, 2006; Nyong et al., 2007; Dube and Sekhwela, 2008; Crate and Nuttal, 2009; Mercer et al., 2009; Roncoli et al., 2009; Green and Raygorodetsky, 2010; Orlove et al., 2010; Crate, 2011; Nakashima et al., 2012; see also Sections 12.3, 12.3.1, 12.3.2, 12.3.3, 12.3.4, 14.4.5, 14.4.7, 15.3.2.7, 25.8.2, 28.2.6.1, 28.4.1). For example, a case study in Labrador (Canada) demonstrated the need to account for local material and symbolic values because they shape the relationship to the land, underlie the way of life, influence the intangible effects of climate change, and can lead to diverging views on adaptations (Wolf et al., 2012). In Kiribati, the integration of local cultural values attached to resources/assets is fundamental to adaptation planning and water management; otherwise technology will not be properly utilized (Kuruppu, 2009).

2.2.1.2. Psychology

Psychology plays a significant role in climate change decision making (Gifford, 2008; Swim et al., 2010; Anderson, 2011). Important psychological factors for decision making include perception, representation, knowledge acquisition, memory, behavior, emotions, and understanding of risk (Böhm and Pfister, 2000; Leiserowitz, 2006; Lorenzoni et al., 2006; Oskamp and Schultz, 2006; Sterman and Sweeney, 2007; Gifford, 2008; Kazdin, 2009; Sundblad et al., 2009; Reser et al., 2011; Swim et al., 2011).

Psychological research contributes to understanding on both risk perception and the process of adaptation. Several theories, such as multi-attribute utility theory (Keeney, 1992), prospect theory (Kahneman and Tversky, 1979; Hardman, 2009), and cumulative prospect theory relate to decision making under uncertainty (Tversky and Kahneman, 1992), especially to risk perception and agency. Adaptation in complex situations pits an unsure gain against an unsure loss, so creates an asymmetry in preference that magnifies with time as gains/losses are expected to accrue in future. Decisions focusing on values and uncertainty are therefore subject to framing effects. Recent cognitive approaches include the one-reason decision process that uses limited data in a limited time period (Gigerenzer and Goldstein, 1996) or decision by sampling theory that samples real-world data to account for the cognitive biases observed in behavioral economics (Stewart et al., 2006; Stewart and Simpson, 2008). Risk perception is further discussed in Section 19.6.1.4.

Responses to new information can modify previous decisions, even producing contradictory results (Grothmann and Patt, 2005; Marx et al., 2007). Although knowledge about climate change is necessary (Milfont, 2012), understanding such knowledge can be difficult (Rajeev Gowda et al., 1997; Boyes et al., 1999; Andersson and Wallin, 2000). Cognitive obstacles in processing climate change information include psychological distances with four theorized dimensions: temporal, geographical, social distance, and uncertainty (Spence et al., 2012; see also Section 25.4.3). Emotional factors also play an important role in climate change perception, attitudes, decision making, and actions (Meijnders et al., 2002; Leiserowitz, 2006; Klöckner and Blöbaum, 2010; Fischer and Glenk 2011; Roeser, 2012) and even shape organizational decision making (Wright and Nyberg, 2012). Other studies on attitudes and behaviors relevant to climate change decision making, include place attachment (Scannell and Gifford, 2013; see also Section 25.4.3), political affiliation (Davidson and Haan, 2011), and perceived costs and benefits (Tobler et al., 2012). Time is a critical component of action-based decision making (Steel and König, 2006). As the benefits of many climate change actions span multiple temporal scales, this can create a barrier to effective motivation for decisions through a perceived lack of value associated with long-term outcomes.

Protection Motivation Theory (Rogers, 1975; Maddux and Rogers, 1983), which proposes that a higher personal perceived risk will lead to a higher motivation to adapt, can be applied to climate change-related problems (e.g., Grothmann and Reusswig, 2006; Cismaru et al., 2011). The person-relative-to-event approach predicts human coping strategies as a function of the magnitude of environmental threat (Mulilis and Duval, 1995; Duval and Mulilis, 1999; Grothmann et al., 2013). People's responses to environmental hazards and disasters are represented in the multistage Protective Action Decision Model (Lindell and Perry, 2012). This model helps decision makers to respond to long-term threat and apply it in long-term risk management. Grothmann and Patt (2005) developed and tested a socio-cognitive model of proactive private adaptation to climate change showing that perceptions of adaptive capacities were important as well as perceptions of risk. If a perceived high risk is combined with a perceived low adaptive capacity (see Section 2.4.2.2; Glossary), the response is fatalism, denial, and wishful thinking.

Best-practice methods for incorporating and communicating information about risk and uncertainties into decisions about climate change (Climate Change Science Program, 2009; Pidgeon and Fischhoff, 2011) suggests that effective communication of uncertainty requires products and processes that (1) closes psychological distance, explaining why this information is important to the recipient; (2) distinguishes between and explains different types of uncertainty; (3) establishes self-agency, explaining what the recipient can do with the information and ways to make decisions under uncertainty (e.g., precautionary principle, iterative risk-management); (4) recognizes that each person's view of risks and opportunities depends on their values; (5) recognizes that emotion is a critical part of judgment; and (6) provides mental models that help recipients to understand the connection between cause and effect. Information providers also need to test their messages, as they may not be communicating what they think they are.

2.2.1.3. Language and Meaning

Aspects of decision making concerned with language and meaning include framing, communication, learning, knowledge exchange, dialog, and discussion. Most IPCC-related literature on language and communication deals with definitions, predictability, and incomplete knowledge, with less emphasis given to other aspects of decision support such as learning, ambiguity, contestedness, and complexity. Three important areas assessed here are definitions, risk language and communication, and narratives.

Decision-making processes need to accommodate both specialist and non-specialist meanings of the concepts they apply. Various disciplines often have different definitions for the same terms or use different terms for the same action or object, which is a major barrier for communication and decision making (Adger, 2003; see also Chapter 21). For example, adaptation is defined differently with respect to biological evolution, climate change, and social adaptation. Budescu et al. (2012) found that people prefer imprecise wording but precise numbers when appropriate. Personal lexicons vary widely, leading to differing interpretations of uncertainty terms (Morgan et al., 1990); in the IPCC's case leading to uncertainty ranges often being interpreted differently than intended (Patt and Schrag, 2003; Patt and Dessai, 2005; Budescu et al., 2012). Addressing both technical and everyday meanings of key terms can help bridge the analytic and emotive aspects of cognition. For example, words like danger, disaster, uncertainty, and catastrophe have technical and emotive aspects (Britton, 1986; Carvalho and Burgess, 2005). Terms where this issue is especially pertinent include adaptation, vulnerability, risk, dangerous, catastrophe, resilience, and disaster. Other words have definitional issues because they contain different epistemological frames; sustainability and risk are key examples (Harding, 2006; Hamilton et al., 2007). Many authors advocate that narrow definitions focused solely on climate need to be expanded to suit the context in which they are being used (Huq and Reid, 2004; O'Brien et al., 2007; Schipper, 2007). This is a key role for risk communication, ensuring that different types of knowledge are integrated within decision context and outlining the different values—implicit and explicit—involved in the decision process (e.g., Morgan, 2002; Lundgren and McMakin, 2013).

The language of risk has a crucial role in framing and belief. Section 2.1.2 described over-arching and climate-specific definitions but risk enters into almost every aspect of social discourse, so is relevant to how risk is framed and communicated (e.g., Hansson, 2004). Meanings of risk range from its ordinary use in everyday language to power and political discourse, health, emergency, disaster, and seeking benefits, ranging from specific local meanings to broad-ranging concepts such as the risk society (Beck and Ritter, 1992; Beck, 2000; Giddens, 2000). Complex framings in the word risk (Fillmore and Atkins, 1992; Hamilton et al., 2007) feature in general English as both a noun and a verb, reflecting harm and chance with negative and positive senses (Fillmore and Atkins, 1992). Problem analysis applies risk as a noun (at-risk), whereas risk management applies risk as a verb (to-risk) (Jones, 2011). For simple risks, this transition is straightforward because of agreement around values and agency (Figure 2-2). In complex situations, risk as a problem and as an opportunity can compete with each other, and if socially amplified can lead to action paralysis (Renn, 2011). For example, unfamiliar adaptation options that seem to be risky themselves will force a comparison between the risk of maladaptation and future climate risks, echoing the risk trap where problems and solutions come into conflict (Beck, 2000). Fear-based dialogs in certain circumstances can cause disengagement (O'Neill and Nicholson-Cole, 2009), by emphasizing risk aversion. Young (2013) proposes framing adaptation as a solution to overcome the limitations of framing through the problem, and links it to innovation, which provides established pathways for the implementation of actions, proposing a problem-solution framework linking decision making to action. Framing decisions and modeling actions on positive risk-seeking behavior can help people to address uncertainty as opportunity (e.g., Keeney, 1992).

Narratives are accounts of events with temporal or causal coherence that may be goal directed (László and Ehmann, 2012) and play a key role in communication, learning, and understanding. They operate at the personal to societal scales, are key determinants of framing, and have a strong role in creating social legitimacy. Narratives can also be non-verbal: visualization, kinetic learning by doing, and other sensory applications can be used to communicate science and art and to enable learning through play (Perlovsky, 2009; Radford, 2009). Narratives of climate change have evolved over time and invariably represent uncertainty and risk (Hamblyn, 2009) being characterized as tools for analysis, communication, and engagement (Cohen, 2011; Jones et al., 2013; Westerhoff and Robinson, 2013) by:

- Providing a social and environmental context to modelled futures (Arnell et al., 2004; Kriegler et al., 2012; O'Neill et al., 2014), by describing aspects of change that drive or shape those futures as part of scenario construction (Cork et al., 2012).
- Communicating knowledge and ideas to increase understanding and increase agency framing it in ways so that actions can be implemented (Juhola et al., 2011) or provide a broader socio-ecological context to specific knowledge (Burley et al., 2012). These narratives bridge the route between scientific knowledge and local understandings of adaptation, often by working with multiple actors in order to creatively explore and develop collaborative potential solutions (Turner and Clifton, 2009; Paton and Fairbairn-Dunlop, 2010; Tschakert and Dietrich, 2010).
- Exploring responses at an individual/institutional level to an aspect of adaptation, and communicating that experience with others (Bravo, 2009; Cohen, 2011). For example, a community that believes itself to be resilient and self-reliant is more likely to respond proactively, contrasted to a community that believes itself to be vulnerable (Farbotko and Lazrus, 2012). Bravo (2009) maintains that narratives of catastrophic risk and vulnerability demotivate indigenous peoples whereas narratives combining scientific knowledge and active citizenship promote resilience (Section2.5.2).

2.2.1.4. Ethics

Climate ethics can be used to formalize objectives, values (Section 2.2.1.1), rights, and needs into decisions, decision-making processes, and actions (see also Section 16.7). Principal ethical concerns include intergenerational equity; distributional issues; the role of uncertainty in allocating fairness or equity; economic and policy decisions; international justice and law; voluntary and involuntary levels of risk; cross-cultural relations; and human relationships with nature, technology, and the sociocultural world. Climate change ethics have been developing over the last 20 years (Jamieson, 1992, 1996; Gardiner, 2004; Gardiner et al., 2010), resulting in a substantial literature (Garvey, 2008; Harris, 2010; O'Brien et al., 2010; Arnold, 2011; Brown, 2012; Thompson and Bendik-Keymer, 2012). Equity, inequity, and responsibility are fundamental concepts in the UNFCCC (UN, 1992) and therefore are important considerations in policy development for CIAV. Climate ethics examine effective responsible and "moral" decision making and action, not only by governments but also by individuals (Garvey, 2008).

An important discourse on equity is that industrialized countries have, through their historical emissions, created a natural debt (Green and

Smith, 2002). Developing nations experience this debt through higher impacts and greater vulnerability combined with limited adaptive capacity. Regional inequity is also of concern (Green and Smith, 2002), particularly indigenous or marginalized populations exposed to current climate extremes, who may become more vulnerable under a changing climate (Tsosie, 2007; see also Section 12.3.3). With respect to adaptation assessment, cost-benefit or cost-effectiveness methods combined with transfer of funds will not satisfy equity considerations (Broome, 2008; see also Section 17.3.1.4) and modifications such as equity-weighting (Kuik et al., 2008) and cost-benefit under uncertainty (Section 17.3.2.1), have not been widely used. Adaptation measures need to be evaluated by considering their equity implications (Section 17.3.1.4) especially under uncertainty (Hansson, 2004).

Intergenerational issues are frequently treated as an economic problem, with efforts to address them through an ethical framework proving to be controversial (Nordhaus, 2007; Stern and Treasury of Great Britain, 2007; Stern, 2008). However, future harm may make the lives of future generations difficult or impossible, dilemmas that involve ethical choices (Broome, 2008), therefore discount rates matter (Section 17.4.4.4). Some authors question whether the rights and interests of future people should even be subject to a positive discount rate (Caney, 2009). Future generations can neither defend themselves within current economic frameworks (Gardiner, 2011) nor can these frameworks properly account for the dangers, interdependency, and uncertainty under climate change (Nelson, 2011), even though people's values may change over time (Section 16.7). The limits to adaptation raise questions of irreversible loss and the loss of unique cultural values that cannot necessarily be easily transferred (Section 16.7), contributing to key vulnerabilities and informing ethical issues facing mitigation (see Section 19.7.1).

Environmental ethics considers the decisions humans may make concerning a range of biotic impacts (Schalow, 2000; Minteer and Collins, 2010; Nanda, 2012; Thompson and Bendik-Keymer, 2012). Intervention in natural systems through "assisted colonization" or "managed relocation" raises important ethical and policy questions (Minteer and Collins, 2010; Section 4.4.2.4) that include the risk of unintended consequences (Section 4.4.4). Various claims are made for a more pragmatic ethics of ecological decision making (Minteer and Collins, 2010), consideration of moral duties toward species (Sandler, 2009), and ethically explicit and defendable decision making (Minteer and Collins, 2005a,b).

Cosmopolitan ethics and global justice can lead to successful adaptation and sustainability (Caney, 2006; Harris, 2010) and support collective decision making on public matters through voting procedures (Held, 2004). Ethics also concerns the conduct and application of research, especially research involving stakeholders. Action-based and participatory research requires that a range of ethical guidelines be followed, taking consideration of the rights of stakeholders, respect for cultural and practical knowledge, confidentiality, dissemination of results, and development of intellectual property (Macaulay et al., 1999; Kindon et al., 2007; Daniell et al., 2009; Pearce et al., 2009). Ethical agreements and processes are an essential part of participatory research, whether taking part as behavioral change processes promoting adaptation or projects of collaborative discovery (*high confidence*). Although the climate change ethics literature is rapidly developing, the related practice of decision making and implementation needs further development. Ethical and equity issues are discussed in WGIII AR5 Chapter 3.

2.2.2. Institutional Context

2.2.2.1. Institutions

Institutions are rules and norms held in common by social actors that guide, constrain, and shape human interaction (North, 1990; Glossary). Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. Organizations—such as parliaments, regulatory agencies, private firms, and community bodies—develop and act in response to institutional frameworks and the incentives they frame (Young et al., 2008). Institutions can guide, constrain, and shape human interaction through direct control, through incentives, and through processes of socialization (Glossary). Virtually all CIAV decisions will be made by or influenced by institutions because they shape the choices made by both individuals and organizations (Bedsworth and Hanak, 2012). Institutional linkages are important for adaptation in complex and multi-layered social and biophysical systems such as coastal areas (Section 5.5.3.2) and urban systems (Section 8.4.3.4), and are vital in managing health (Section 11.6), human security (Sections 12.5.1, 12.6.2), and poverty (Section 13.1). Institutional development and interconnectedness are vital in mediating vulnerability in social-ecological systems to changing climate risks, especially extremes (Chapters 5, 7 to 9, 11 to 13).

The role of institutions as actors in adaptation are discussed in Section 14.4, in planning and implementing adaptation in Section 15.5, and in providing barriers and opportunities in Section 16.3. Their roles can be very diverse. Local institutions usually play important roles in accessing resources and in structuring individual and collective responses (Agarwal, 2010; see also Section 14.4.2) but Madzwamuse (2010) found that in Africa, state-level actors had significantly more influence on formal adaptation policies than did civil society and local communities. This suggests a need for greater integration and cooperation among institutions of all levels (Section 15.5.1.2). Section 14.2.3 identifies four institutional design issues: flexibility; potential for integration into existing policy plans and programs; communication, coordination, and cooperation; and the ability to engage with multiple stakeholders.

Institutions are instrumental in facilitating adaptive capacity, by utilizing characteristics such as variety, learning capacity, room for autonomous change, leadership, availability of resources, and fair governance (Gupta et al., 2008). They play a key role in mediating the transformation of coping capacity into adaptive capacity and in linking short and long-term responses to climate change and variability (Berman et al., 2012). Most developing countries have weaker institutions that are less capable of managing extreme events, increasing vulnerability to disasters (Lateef, 2009; Biesbroek et al., 2013). Countries with strong functional institutions are generally assumed to have a greater capacity to adapt to current and future disasters. However, Hurricane Katrina of 2005 in the USA and the European heat wave of 2003 demonstrate that strong institutions and other determinants of adaptive capacity do not necessarily reduce vulnerability if these attributes are not translated to actions (IPCC, 2007a; see also Box 2-1, Section 2.4.2.2).

To facilitate adaptation under uncertainty, institutions need to be flexible enough to accommodate adaptive management processes such as evaluation, learning, and refinement (Agarwal, 2010; Gupta et al., 2010; see also Section 14.2.3). Organizational learning can lead to significant change in organizations' purpose and function (Bartley, 2007), for example, where non-governmental organizations have moved from advocacy to program delivery with local stakeholders (Ziervogel and Zermoglio, 2009; Kolk and Pinkse, 2010; Worthington and Pipa, 2010).

Boundary organizations are increasingly being recognized as important to CIAV decision support (Guston, 2001; Cash et al., 2003; McNie, 2007; Vogel et al., 2007). A boundary organization is a bridging institution, social arrangement, or network that acts as an intermediary between science and policy (Glossary). Its functions include facilitating communication between researchers and stakeholders, translating science and technical information, and mediating between different views of how to interpret that information. It will also recognize the importance of location-specific contexts (Ruttan et al., 1994); provide a forum in which information can be co-created by interested parties (Cash et al., 2003); and develop boundary objects, such as scenarios, narratives, and model-based decision support systems (White et al., 2010). Adaptive and inclusive management practices are considered to be essential, particularly in addressing wicked problems such as climate change (Batie, 2008). Boundary organizations also link adaptation to other processes managing global change and sustainable development.

Boundary organizations already contributing to regional CIAV assessments include the Great Lakes Integrated Sciences and Assessments Center in the USA (GLISA; http://www.glisa.umich.edu/); part of the Regional Integrated Sciences and Assessments Program of the U.S. government (RISA; Pulwarty et al., 2009); the UK Climate Impacts Program (UKCIP; UK Climate Impacts Program, 2011); the Alliance for Global Water Adaptation (AGWA; http://alliance4water.org); and institutions working on water issues in the USA, Mexico, and Brazil (Kirchhoff et al., 2012; Varady et al., 2012).

2.2.2.2. Governance

Effective climate change governance is important for both adaptation and mitigation and is increasingly being seen as a key element of risk management (*high confidence*) (Renn, 2008; Renn et al., 2011). Some analysts propose that governance of adaptation requires knowledge of anticipated regional and local impacts of climate change in a more traditional planning approach (e.g., Meadowcroft, 2009), whereas others propose governance consistent with sustainable development and resilient systems (Adger, 2006; Nelson et al., 2007; Meuleman and in 't Veld, 2010). Quay (2010) proposes "anticipatory governance"—a flexible decision framework based on robustness and learning (Sections 2.3.3, 2.3.4). Institutional decisions about climate adaptation are taking place within a multi-level governance system (Rosenau, 2005; Kern and Alber, 2008). Multi-level governance could be a barrier for successful adaptation if there is insufficient coordination as it comprises different regulatory, legal, and institutional systems (Section 16.3.1.4), but is required to manage the "adaptation paradox" (local solutions to a global problem), unclear ownership of risks and the adaptation bottleneck linked to difficulties with implementation (Section 14.5.3). Lack of horizontal and vertical integration between organizations and policies leads to insufficient risk governance in complex social-ecological systems such as coasts (Section 5.5.3.2) and urban areas (Section 8.4), including in the management of compound risks (Section 19.3.2.4).

Legal and regulatory frameworks are important institutional components of overall governance, but will be challenged by the pervasive nature of climate risks (*high confidence*) (Craig, 2010; Ruhl, 2010a,b). Changes proposed to manage these risks better under uncertainty include integration between different areas of law, jurisdictions and scale, changes to property rights, greater flexibility with respect to adaptive management, and a focus on ecological processes rather than preservation (Craig, 2010; Ruhl, 2010a; Abel et al., 2011; Macintosh et al., 2013). Human security in this report is not seen just as an issue of rights (Box 12-1), given that a minimum set of universal rights exists (though not always exercised), but is instead assessed as being subject to a wide range of forces. Internationally, sea level rise could alter the maritime boundaries of many nations that may lead to new claims by affected nations or loss of sovereignty (Barnett and Adger, 2003). New shipping routes, such as the North West Passage, will be opened up by losses in Arctic sea ice (Sections 6.4.1.6, 28.2.6). Many national and international legal institutions and instruments need to be updated to face climate-related challenges and decision implementation (*medium confidence*) (Verschuuren, 2013).

2.3. Methods, Tools, and Processes for Climate-related Decisions

This section deals with methods, tools, and processes that deal with uncertainties (Section 2.3.1); describes scenarios (Section 2.3.2); covers trade-offs and multi-metric valuation (Section 2.3.3); and reviews learning and reframing (Section 2.3.4).

2.3.1. Treatment of Uncertainties

Most advice on uncertainty, including the latest guidance from the IPCC (Mastrandrea et al., 2010; see also Section 1.1.2.2), deals with uncertainty in scientific findings and to a lesser extent confidence. Although this is important, uncertainty can invade all aspects of decision making, especially in complex situations. Whether embodied in formal analyses or in the training and habits of decision makers, applied management is often needed because unaided human reasoning can produce mismatches between actions and goals (Kahneman, 2011). A useful high-level distinction is between ontological uncertainty—what we know—and epistemological uncertainty—how different areas of knowledge and "knowing" combine in decision making (van Asselt and Rotmans, 2002; Walker et al., 2003). Two other areas of relevance are ambiguity (Brugnach et al., 2008) and contestedness (Klinke and Renn, 2002; Dewulf et al., 2005), commonly encountered in wicked problems/systemic risks (Renn and Klinke, 2004; Renn et al., 2011).

Much of this uncertainty can be managed through framing and decision processes. For example, a predict-then-act framing is different to an assess-risk-of-policy framing (SREX Section 6.3.1 and Figure 6.2; Lempert et al., 2004). In the former, also known as "top-down," model or impacts-first, science-first, or standard approach, climate or impact uncertainty is described independently of other parts of the decision problem. For instance, probabilistic climate projections (see Figure 21-4 or WGI AR5 Chapters 11 and 12; Murphy et al., 2009) are generated for wide application, and thus are not tied to any specific choice. This follows the cause and effect model described in Section 2.1. The basic structure of IPCC Assessment Reports follows this pattern, with WGI laying out what is known and uncertain about current and future changes to the climate system. Working Groups II and III then describe impacts resulting from and potential policy responses to those changes (Jones and Preston, 2011).

In contrast, the "assess-risk-of-policy" framing (Lempert et al., 2004; UNDP, 2005; Carter et al., 2007; Dessai and Hulme, 2007) starts with the decision-making context. This framing is also known as "context-first" (Ranger et al., 2010); "decision scaling" (Brown et al., 2011); "bottom-up"; vulnerability, tipping point (Kwadijk et al., 2010); critical threshold (Jones, 2001); or policy-first approaches (SREX Section 6.3.1). In engaging with decision makers, the "assess-risk-of-policy" approach often requires information providers work closely with decision makers to understand their plans and goals, before customizing the uncertainty description to focus on those key factors. This can be very effective, but often needs to be individually customized for each decision context (Lempert and Kalra, 2011; Lempert, 2012) requiring collaboration between researchers and users (see Box 2-1). A "predict-then-act" framing is appropriate when uncertainties are shallow, but when uncertainties are deep, an "assess-risk-of-policy" framing is more suitable (Dessai et al., 2009).

The largest focus on uncertainty in CIAV has been on estimating climate impacts such as streamflow or agricultural yield changes and their consequent risks. Since AR4, the treatment of these uncertainties has advanced considerably. For example, multiple models of crop responses to climate change have been compared to estimate inter-model uncertainty (Asseng et al., 2013). Although many impact studies still characterize uncertainty by using a few climate scenarios, there is a growing literature that uses many climate realizations and also assesses uncertainty in the impact model itself (Wilby and Harris, 2006; New et al., 2007). Some studies propagate uncertainties to evaluate adaptation options locally (Dessai and Hulme, 2007) by assessing the robustness of a water company's plan to climate change uncertainties or regionally (Lobell et al., 2008) by identifying which regions are most in need of adaptation to food security under a changing climate. Alternatively, the critical threshold approach, where the likelihood of a given criterion can be assessed as a function of climate change, is much less sensitive to input uncertainties than assessments estimating the "most likely" outcome (Jones, 2010). This is one of the mainstays of robustness assessment discussed in Section 2.3.3.

2.3.2. Scenarios

A scenario is a story or image that describes a potential future, developed to inform decision making under uncertainty (Section 1.1.3). A scenario is not a prediction of what the future will be but rather a description of how the future might unfold (Jäger et al., 2008). Scenario use in the CIAV research area has expanded significantly beyond climate into broader socioeconomic areas as it has become more mainstream (*high confidence*) (Sections 1.1.3, 2.4.2.1). Climate change has also become a core feature of many scenarios used in regional and global assessments of environmental and socioeconomic change (Carpenter et al., 2005; Raskin et al., 2005). Scenarios can be used at a number of stages within an assessment process or can underpin an entire assessment. They serve a variety of purposes, including informing decisions under uncertainty, scoping and exploring poorly understood issues, and integrating knowledge from diverse domains (Parson et al., 2007; Parson, 2008).

Scenarios also contribute to learning and discussion, facilitate knowledge exchange, and can be expressed using a range of media. Local scale visualization of impacts and adaptation measures, depicted on realistic landscapes, is an emerging technology that is being tested to support dialog on adaptation planning at the local scale (Schroth et al., 2011; Sheppard, 2012). Although visual representations of scenario-based impact assessments may be available for a location, scenario-based adaptation assessments usually are not. Artistic depictions of potential adaptation measures and outcomes are being negotiated and assessed with local stakeholders in communities within Metro Vancouver, Canada (Shaw et al., 2009; Burch et al., 2010; Sheppard et al., 2011).

Climate, socioeconomic, or other types of scenarios are widely used to assess the impacts of climate change. Fewer studies report on the use of scenarios as participatory tools to enable decision making on adaptation (e.g., Harrison et al., 2013). However, the scenario literature emphasizes the importance of process over product. The new generation of climate and socioeconomic scenarios being developed from the Representative Concentration Pathways (RCPs; 1.1.3.1) and Shared Socioeconomic Pathways (SSPs; 1.1.3.2), which are storylines corresponding to the new RCPs (Moss et al., 2010; Kriegler et al., 2012) have yet to be applied within CIAV studies in any substantive way (van Ruijven et al., 2013; Ebi et al., 2014).

By separating risks into simple and systemic or wicked-problem risks, scenario needs for decision making can be better identified (*medium confidence*). For simple risks, if probabilities cannot be easily calculated then scenarios can be used to explore the problem, test for acceptable or unacceptable levels of risk, and illustrate alternative solutions for evaluation and testing. Wicked problems will need to be thoroughly scoped to select the most suitable decision-making process, with scenarios playing an important role. They may require separate applications of problem (exploratory or descriptive) and solution-based (normative or positive) scenarios or the development of reflexive scenarios, the latter being updated with new knowledge over time that may re-examine values and goals (van Notten, 2006; Wilkinson and Eidinow, 2008; Jones, 2012); these categories can also be structured as top-down, bottom-up, and interactive (Berkhout et al., 2013). Even if conditional probabilities can be used to illustrate climate futures, scenarios are needed to explore the solutions space involving strategic actions, options planning, and governance using process and goal-oriented methods (*high confidence*).

2.3.3. Evaluating Trade-offs and Multi-metric Valuation

Decision makers bring diverse aims, interests, knowledge, and values to CIAV decision making. With effective decision support, parties to a decision can manage competing views by more clearly articulating their goals; understanding how various options affect trade-offs between goals; and making informed choices that participants regard as legitimate, salient, and credible (*high confidence*) (Cash et al., 2003). The decision theory, risk governance, and ethical reasoning literatures use two broad sets of criteria for decision making: outcome-based criteria focus on whether a decision is likely to meet specified goals; process-based criteria compare alternative actions according to the process by which a decision is arrived. In particular, decision process aims to help stakeholders choose between the risks, costs, and obligations being proposed (Morgan et al., 1990), including specified levels of risk tolerance. Such choices around risk tolerance, including acceptable levels of risk, are ethical choices (DesJardins, 2012; Nanda, 2012). Selection strategies informing context and process are described in Section 14.3.5. Decision criteria inform the discussions of adaptation options, planning, and economics in Chapters 14 to 17 and WGIII AR5 Chapter 2.

Multi-attribute decision theory (Keeney and Raiffa, 1993), or multi-criteria decision analysis (MCDA), provides the most general framework for assessing outcomes-based criteria. MCDA concepts and tools organize and display the implications of alternative decisions on differing objectives (e.g., cost and environmental quality), order and test preferences among trade-offs between potentially incommensurate objectives, and show how alternative processes for choosing options can lead to different decisions. Cost-benefit analysis under uncertainty, one key tool for evaluating trade-offs, is described in Section 17.3.2.1. Simple MCDA tools include scorecards that graphically display how alternative policy choices affect different goals. For example, the "burning embers" diagram displays how risks to various attributes (e.g., health of unique systems, extreme weather events) depend on targets for a given global mean temperature increase (Figure 19-5). More sophisticated MCDA tools can optimize a portfolio of choices in a variety of ways; for example, one recent method applies scenarios representing significant uncertainty to optimize between four or more choices in order to identify robust combinations and system vulnerabilities (Kasprzyk et al., 2013). Successful use of MCDA in CIAV decisions include the U.S. Bureau of Reclamation helping stakeholders with diverse interests and values to consider 26 alternative performance measures for the Colorado River system, to agree on potential climate-related risks, and to consider options for reducing those risks. Trade-offs also occur where adaptation measures produce negative impacts in other areas of value—for example, where adaptation in agricultural and urban areas negatively affect ecosystems (Section 4.3.3.3). Korteling et al. (2013) assess the robustness of adaptation options for six criteria including risk of water shortage, environmental impact, local self-sufficiency, cost, carbon footprint, and social acceptability. Chapter 17 describes many criteria commonly used in MCDA analyses.

Robustness is often nominated as the most appropriate criterion for managing large decision uncertainty. It is a satisficing (sufficient rather than optimal) criterion (Rosenhead, 1989) that seeks decisions likely to perform well over a wide range of plausible climate futures, socioeconomic trends, and other factors (Dessai and Hulme, 2007; Groves et al., 2008; Wilby and Dessai, 2010; WUCA, 2010; Brown et al., 2011; Lempert and Kalra, 2011). Robust decisions often perform better than other methods if the future turns out differently than expected. Testing for robustness can often illuminate trade-offs that help decision makers achieve consensus even when they have different future expectations. Robust choices often trade some optimality for being able to manage unanticipated outcomes. Many forms of the precautionary principle are consistent with robustness criteria (Lempert and Collins, 2007). Flexible and reversible options are often needed to manage situations with significant potential for unanticipated outcomes and differences in values and interests among decision makers (Gallopín, 2006; Hallegatte, 2009; see also Sections 2.3.4, 5.5.3.1). Flexibility is signaled by reaching of specific management thresholds, critical control points, or design states (Box 5-1). The literature disagrees on the relationship between robustness and resilience (Folke, 2006). Chapter 20 describes resilience as a property of systems that might be affected by decision makers' choices, while robustness is a property of the choices made by those decision makers (SREX Chapter 1).

Process-based criteria focus on the credibility and legitimacy of a decision process. Institutional (Section 2.2.2) and cultural and ethical (Section 2.2.1) contexts will strongly influence the appropriateness and importance of such criteria in a given situation (*high confidence*). Process criteria provide institutional rules, and governance for decision making in a wide range of circumstances (Dietz and Stern, 2008; Sen, 2009). For instance, many environmental laws require advanced notice and periods of public comment before any regulations are issued. Water rights can be made tradable, giving users extra flexibility during times of water shortage or oversupply. Participants may regard any decision that fails to respect such rights as illegitimate. In complex situations of a collaborative nature, both outcome and process-related criteria will be needed in a decision-making process (*high confidence*).

Stakeholder involvement is a central process for climate-related decision making and since the AR4 has grown in importance, particularly for adaptation decision making (e.g., Lebel et al., 2010), covering methods (Debels et al., 2009; Gardner et al., 2009; Salter et al., 2010; André et al., 2012) and reflecting concrete experiences with stakeholder involvement in CIAV assessments and adaptation processes (de la Vega-Leinert et al., 2008; Ebi and Semenza, 2008; Posthumus et al., 2008; Raadgever et al., 2008; Tompkins et al., 2008a,b; Preston et al., 2009). Lebel et al. (2010) differentiate six advantages of social learning and stakeholder involvement for adaptation to climate change: (1) reduces informational uncertainty; (2) reduces normative uncertainty; (3) helps to build consensus on criteria for monitoring and evaluation; (4) can empower stakeholders to influence adaptation and take appropriate actions themselves by sharing knowledge and responsibility in participatory processes; (5) can reduce conflicts and identify synergies between adaptation activities of various stakeholders, thus improving overall chances of success; and (6) can improve the likely fairness, social justice, and legitimacy of adaptation decisions and actions by addressing the concerns of all relevant stakeholders. Complex settings will require a detailed mapping of stakeholder roles and responsibilities (André et al., 2012).

2.3.4. Learning, Review, and Reframing

Effective decision support processes generally include learning, where learning and review become important to track decision progress (National Research Council, 2009b; see also Box 2-1, Figure 2-1). This can be achieved by developing an ongoing monitoring and review process

Frequently Asked Questions

FAQ 2.2 | Which is the best method for climate change decision making/assessing adaptation?

No single method suits all contexts, but the overall approach used and recommended by the IPCC is iterative risk management. The International Standards Organization defines risk as the effect of uncertainty on objectives. Within the climate change context, risk can be defined as the potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain. Risk management is a general framework that includes alternative approaches, methodologies, methods, and tools. Although the risk management concept is very flexible, some methodologies are quite prescriptive—for example, legislated emergency management guidelines and fiduciary risk. At the operational level, there is no single definition of risk that applies to all situations. This gives rise to much confusion about what risk is and what it can be used for.

Simple climate risks can be assessed and managed by the standard methodology of making up the "adaptation deficit" between current practices and projected risks. Where climate is one of several or more influences on risk, a wide range of methodologies can be used. Such assessments need to be context-sensitive, to involve those who are affected by the decision (or their representatives), to use both expert and practitioner knowledge, and to map a clear pathway between knowledge generation, decision making, and action.

during the scoping stage of a project or program. If circumstances change so much that desired outcomes may not be achieved, then reframing of the decision criteria, process, and goals may be required. This iterative approach begins with the many participants to a decision working together to define its objectives and other parameters, working with experts to generate and interpret decision-relevant information, then revisiting the objectives and choices based on that information (Figure 2-1). Again, process is important. Pelling et al. (2008) found that accounting for different personal values in both an official and informal capacity could enhance social learning and therefore adaptive capacity. Measuring progress on adaptation and adaptive capacity by tracking impacts, vulnerability, and related adaptation metrics and process indicators is discussed in Section 14.6. Such metrics are needed to transfer wider learning on adaptation to new situations.

Learning and review can range from periodic reporting to adaptive management. Adaptive management refers to a choice of policy required to generate reliable new information (Holling, 1978, 1996) and involves a process of adjusting approaches in response to observations of their effect and changes in the system brought on by resulting feedback effects and other variables (Glossary). Adaptive strategies are designed to be robust over a wide range of futures by evolving over time in response to new information (Rosenhead, 1989; Walker et al., 2001; Lempert and Schlesinger, 2002; Swanson et al., 2006). Necessary components include separating immediate actions from those that can be deferred (and that may require additional information); an explicit process to generate new information; institutional mechanisms for incorporating and acting on new information; and some understanding of the policy limits that, if exceeded, should lead to its re-evaluation (Swanson et al., 2012; see also Box 5-1). As indicated by Figure 2-1, effective decision making not only requires flows of appropriate information but people willing and able to act on it. Though most policies change over time, very few follow the steps of an intentional adaptive strategy (*high confidence*). For instance, McCray et al. (2010) surveyed 32 examples of U.S. environmental, health, and safety regulations—all legally required to be adaptive—and found only five instances where any policy change occurred as intended.

Reframing of an action can occur when an existing set of decisions and actions are failing to manage risks adequately (see Box 2-1). Based on experience to date, there now exists a sufficiently rich set of available methods, tools, and processes to support effective CIAV decisions in a wide range of contexts (*medium confidence*), although they may not be combined appropriately, accessible, or readily used by decision makers (Webb and Beh, 2013). Tools for decision making, planning and development, and transfer and diffusion are discussed in Section 15.4.

2.4. Support for Climate-related Decisions

Growing understanding of the aspects of decision making (Section 2.2) and methods and tools (Section 2.3) have led to improved support for CIAV decisions, as shown by the provision of climate information and services (Section 2.4.1), methods for impacts and vulnerability assessments (Section 2.4.2), and decision support in practice (Section 2.4.3). Figure 2-3 divides the decision-making process into four stages: scoping, analysis, implementation and review, outlining institutional, leadership, knowledge, and information characteristics for each stage. Most effort in CIAV research has been put into the first two stages, whereas decision implementation and follow-up have been minimal. This does not imply that the analysis stage is discounted. Problem analysis and solution evaluation are significant undertakings in any decision process, but that is where most current climate change assessments stop. Note that each of these stages can be divided into other quite distinct process elements.

2.4.1. Climate Information and Services

Climate services are institutions that bridge generation and application of climate knowledge. History and concepts are described in Section

Box 2-1 | Managing Wicked Problems with Decision Support

A well-designed decision support process, combined with favorable political conditions, can effectively address "wicked" (Section 2.1) decision challenges. The State of Louisiana faces a serious problem of coastal land loss, exposing the region's fisheries and heightening the risk of storm surge damage to the City of New Orleans, one of the USA's largest ports with facilities that account for ~20% of U.S. oil and gas production (Coastal Protection and Restoration Authority, 2007). Previous efforts at comprehensive coastal protection had been stymied by, among other factors, numerous competing jurisdictions and stakeholders with a wide range of conflicting interests.

In the aftermath of Hurricane Katrina, the state embarked on a new coastal planning effort, this time with extensive decision support. The Coastal Protection and Restoration Authority organized an extension decision support effort with a network of research institutions interacting with a 33-member stakeholder group consisting of representatives from business and industry; federal, state, and local governments; non-governmental organizations; and coastal institutions. In dozens of workshops over the course of 2 years, these stakeholders influenced the development of and interacted with a decision support system consisting of (1) a regional model that integrated numerous strands of scientific data into projections of future flood risk (Fischbach et al., 2012) and (2) a multi-attribute planning tool that allowed stakeholders to explore the implications of alternative portfolios of hundreds of proposed risk reduction projects over alternative sea level rise scenarios (Groves et al., 2012). This decision support system allowed decision makers and stakeholders to first formulate alternative risk reduction plans then to visualize outcomes and trade-offs up to 50 years into the future.

The resulting Master Plan for a Sustainable Coast passed the state legislature by a unanimous vote in May 2012. Deviating strongly from past practice, the plan allocates far more resources to restoring natural barriers than to structural measures such as levees. The plan balances the interests of multiple stakeholders and contains some projects that offer near-term benefits and some whose benefits will be largely felt decades from now. Observers recognized that extensive analytic decision support contributed significantly to this plan.

2.4.1.1, how decision support applied in Section 2.4.1.2, and the policy implications of climate services as a global practice in Section 2.4.1.3. These institutions supply climate information on local, regional, national, and global scales for the monitoring of risks, mitigation, and adaptation planning as an important component of sustainable development (Sivakumar et al., 2011). The Global Framework for Climate Services (Hewitt et al., 2012) aims to "enable better management of the risks of climate variability and change and adaptation to climate change, through the development and incorporation of science-based climate information and prediction into planning, policy, and practice on the global, regional, and national scale" (http://www.wmo.int/pages/gfcs/index_en.php). Climate services focus on the connection between climate science and the public demand for information; however, their development and deployment needs support from many other disciplines (Miles et al., 2006). This extended reach requires measures such as case-specific communication, engagement, and knowledge exchange skills (*high confidence*).

While many countries have already established national and regional climate services or are on the way to doing so, they show significant differences. The development of Regional Climate Services in the USA and parts of Europe, with their increasing focus on communication and decision support, is well documented (DeGaetano et al., 2010; von Storch et al., 2011). Developing countries are becoming increasingly aware of the need for climate services (Semazzi, 2011), which is in part reflected in the migration of regional climate models into those countries. In 2001 only around 21 (mostly Organisation for Economic Co-operation and Development (OECD)) countries were running regional climate models (RCMs), but today more than 100 countries are trained in using the Providing REgional Climates for Impact Studies (PRECIS) RCM (Jones et al., 2004; Edwards, 2010). Regional climate services are expanding geographically, shifting from simple understandings of climate cause and effect to ever more complex and wicked problem situations and are becoming more interdisciplinary.

2.4.1.1. Climate Services: History and Concepts

Early climate services in North America were seen as an expansion of weather services, dealing mainly with forecasts, seasonal outlooks, and risk assessment in a mostly stationary but variable climate (Changnon et al., 1990; Miles et al., 2006; DeGaetano et al., 2010). This mainly technical outlook had limited effectiveness; for example, decision makers had difficulties understanding and using climate data for planning purposes (Changnon et al., 1990; Miles et al., 2006; Visbeck, 2008) and the data were slow to access and of poor quality (Changnon et al., 1990). As these services developed, formal definitions of their mission and scope shifted to being user-centric, focusing on active research, data stewardship and effective partnership (National Research Council, 2001). Climate services were understood as a clearinghouse and technical access point to stakeholders, providing education and user access to experts—the latter informing the climate forecast community of information needs, largely to inform adaptation (Miles et al., 2006).

Downscaling is a key product demanded by users for decision making (Section 21.3.3.2). For example, in Africa, regional climate models play an increasing role in Regional Climate Outlook Forums arranged by the

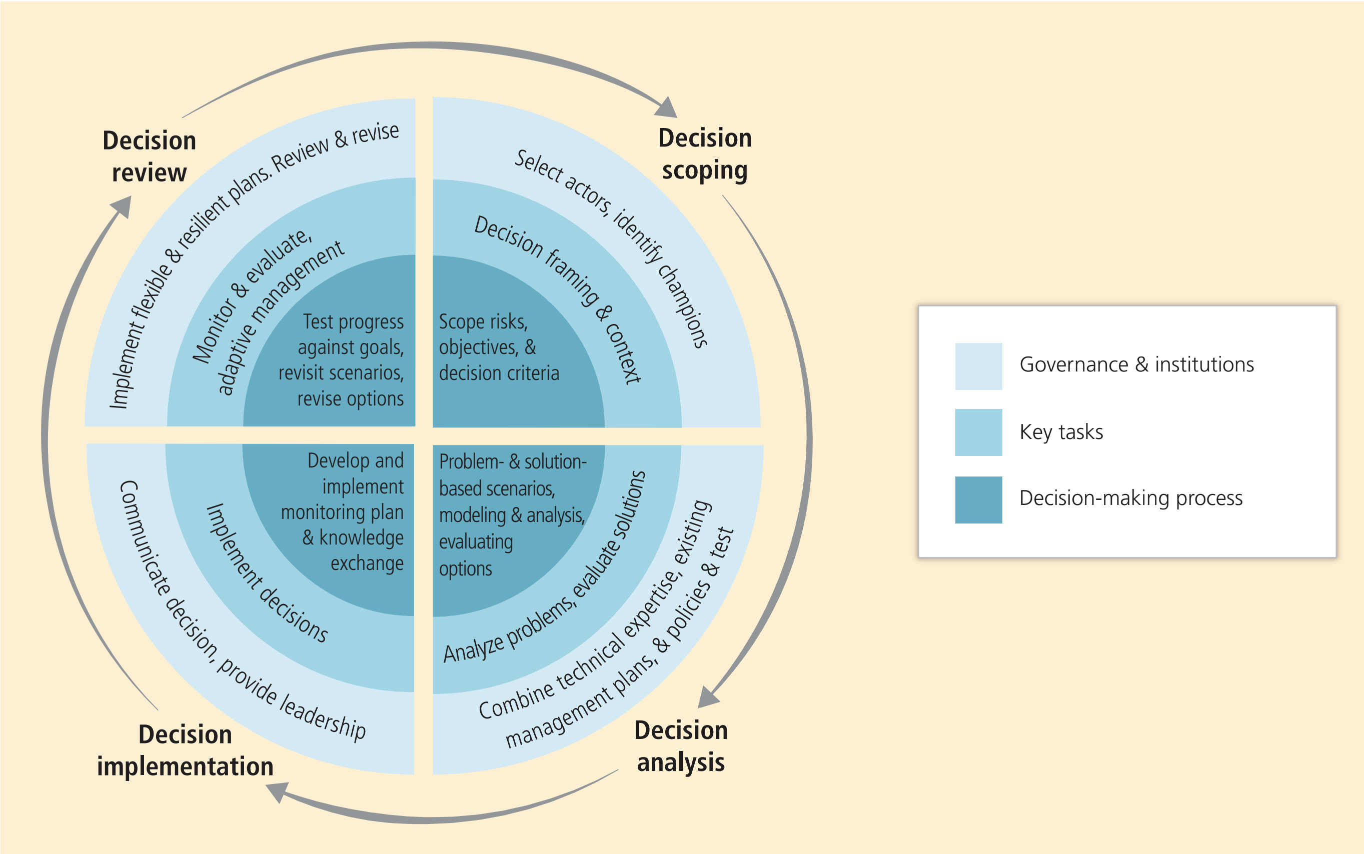


Figure 2-3 | Four-stage process of decision making. Note that while adaptive management is located in the decision review quadrant here, when applied it will influence the entire process.

World Meteorological Organization (WMO). The Global Framework for Climate Services was created in order to coordinate and strengthen activities and develop new infrastructure where needed, focusing on developing countries (WMO, 2011; Hewitt et al., 2012). From initially being supply-focused and static, public climate services increasingly need communication skills, engagement, and knowledge exchange in a highly challenging environment of technical and institutional networks, monitoring systems, and collaborations with other institutions, stakeholders, and decision makers (DeGaetano et al., 2010).

2.4.1.2. Climate Services: Practices and Decision Support

Decision support is generally acknowledged as an integral part of climate services (*high confidence*) (Miles et al., 2006; DeGaetano et al., 2010). Depending on the stage and context in question (see Section 2.1.3.), "best" data as framed by experts should be reconciled with user needs in order to produce scientific information that is relevant and suitable for decision making. Social and cultural determinants have to be taken into account (see Section 2.2) and require the communication of scientific data to be context-specific. Decision support for climate services consists of "processes of interaction, different forms of communication, potentially useful data sets or models, reports and training workshops, data ports and websites, engaging any level of governance, at any stage in the policy- or decision-making process" (Moser, 2009, p. 11). The climate service is a "process of two-way communication" and "involves providing context that turns data into information" (Shafer, 2004). Capacity building is required on all sides of the communication process. For regional climate services, a successful learning process engages both users and providers of knowledge in knowledge exchange. For example, the uptake and utility of climate forecasts in rural Africa is described in Box 9-4.

As knowledge brokers, climate services have to establish an effective dialog between science and the public (von Storch et al., 2011). This dialog undertakes two main tasks: One is to understand the range of perceptions, views, questions, needs, concerns, and knowledge in the public and among stakeholders about climate, climate change, and climate risks; the other task is to convey the content of scientific knowledge to the public, media, and stakeholders. This includes communicating the limitations of such knowledge, the known uncertainties, and the unknowable, as well as the appropriate role of science in complex decision processes (von Storch et al., 2011).

2.4.1.3. The Geo-political Dimension of Climate Services

Climate knowledge is continually being documented and assessed by the social sciences within a policy-relevant context (Yearley, 2009; Grundmann and Stehr, 2010). One focus is on the spread of climate knowledge into developing countries. Climate models distributed to users with no in-house capacity for model development build capacity in regional climate science, producing high-resolution data for local decision making. This mobility of knowledge has far-reaching implications for how climate knowledge is produced; strengthening the influence of epistemic communities such as the IPCC and other global governance mechanisms (Mahony and Hulme, 2012). Thus, while regional climate models play an increasingly important role in decision-making processes, critics argue that climate monopolizes planning and development strategies, rendering other forms of knowledge subordinate to this "climate reductionism" (Dessai et al., 2009; Hulme, 2011).

Indigenous forms of knowledge—including the specialized knowledge of any stakeholder—are becoming increasingly relevant for climate services (*high confidence*) (Strauss and Orlove, 2003; Crate and Nuttal, 2009; Crate, 2011; Ulloa, 2011; Krauss and von Storch, 2012). Local forms of knowledge and scientific climate models are not necessarily mutually exclusive; individual case studies show how both forms of knowledge contribute jointly to place-based adaptation (Strauss and Orlove, 2003; Orlove and Kabugo, 2005; Orlove, 2009; Strauss, 2009; Orlove et al., 2010). Indigenous knowledge in the form of oral histories and other traditional knowledge are being compared or combined with remote sensing technologies and model-based scenarios to co-produce new knowledge, and to create a new discourse on adaptation planning (Nakashima et al., 2012; see also Table 15-1). The challenge will be to collaborate in a way that enables their integration into a shared narrative on future adaptation choices.

These examples show that adaptation needs both to be implemented locally and to be informed by larger scale (inter-)national policies and directions. One strategy will not suit every location. Endfield (2011) argues for a "reculturing and particularizing of climate discourses" in order to successfully localize global and scientific meta-narratives. Climate service development combines very different types of knowledge and the social, cultural, and communication sciences play a decisive role in this process (Pidgeon and Fischhoff, 2011; von Storch et al., 2011). To position itself and to react according to the diverse demands, science-based climate services have to become "rooted in society" (Krauss, 2011). The climate science community does not necessarily take the lead, but becomes part of an inter- and trans-disciplinary process, where politics, culture, religion, values, and so forth become part of climate communication (*medium confidence*).

2.4.2. Assessing Impact, Adaptation, and Vulnerability on a Range of Scales

CIAV assessments address the "adapt to what" question, which can enable a dialog among practitioners, stakeholders, and the public on planning and implementation of adaptation measures within prevailing mechanisms for governance. To date, however, assessments have focused more on I than A (see Figure 1-1d). A number of global initiatives are taking place to enable knowledge generation, transfer, and use, including the Programme of Research on Climate Change Vulnerability, Impacts and Adaptation (PROVIA; http://www.provia-climatechange.org/), the Nairobi Work Programme on impacts, vulnerability, and adaptation to climate change (http://unfccc.int/adaptation/nairobi_work_programme/items/3633.php), and work by the World Bank and regional development banks (http://climatechange.worldbank.org/).

2.4.2.1. Assessing Impacts

For scenario-based impact assessments to contribute to vulnerability and risk assessment, a series of translations need to be performed. Scenarios of projected GHG concentrations are converted to changes in climate, impacts are assessed, perhaps with autonomous adaptation, leading to the evaluation of various adaptation options. This series of translations requires the transformation of data across various scales of time and space, between natural and social sciences, utilizing a wide variety of analytical tools representing areas such as agriculture, forestry, water, economics, sociology, and social-ecological systems. Climate scenarios are translated into scenarios or projections for biophysical and socioeconomic impact variables such as river flow, food supply, coastal erosion, health outcomes, and species distribution (e.g., European Climate Adaptation Platform, http://climate-adapt.eea.europa.eu). Climate services help establish and support the translation process (Section 2.4.1).

The resulting climate impacts and risks are then subject to decision making on risk management and governance. Assessments of observed events combine biophysical and socioeconomic assessments of the past and present (Table 2-1, top row). Most scenario-based assessments superimpose biophysical "futures" onto present-day socioeconomic conditions (Table 2-1, middle row). This is useful for assessing how current socioeconomic conditions may need to change in response to biophysical impacts but raises inconsistencies when future socioeconomic states are out of step with biophysical states. This will hamper assessments of future adaptation responses in coupled social-ecological systems (see Chapter 16). An important challenge, therefore, is to construct impact assessments in which biophysical futures are coupled with socioeconomic futures (Table 2-1, bottom row). A new set of socioeconomic futures, known as Shared Socioeconomic Pathways (SSPs), which are storylines corresponding to the new RCPs (Moss et al., 2010; Kriegler et al., 2012), is being developed to assist this process (Section 1.1.3.2).

A new generation of assessments links biophysical, economic, and social analysis tools in order to describe the interactions between projected biophysical changes and managed systems. For example, Ciscar et al. (2011) estimated the costs of potential climate change impacts, without public adaptation policies, in four European market sectors (agriculture, river floods, coastal areas, and tourism) and one nonmarket sector

Table 2-1 | Nature of published Impact, Adaptation, and Vulnerability (IAV) assessments.

Nature of IAV assessments	Biophysical conditions	Socioeconomic conditions
Stationarity and extrapolation	Continuation of current trends; no change in statistical properties	No change from current conditions
Transitional	Scenario-based projections of future biophysical conditions	No change from current conditions; sometimes sensitivity analysis with alternate futures
Coupled and interactive	Scenario-based projections of future biophysical conditions	Alternative futures from scenarios/storylines consistent with biophysical projections, sometimes with dynamic response

(human health). A similar study in the UK was conducted for tourism, health and transportation maintenance, buildings and transportation infrastructure, and residential water supplies (Hunt, 2008). In the USA, Backus et al. (2013) assessed national and state level gross domestic product (GDP) and employment impacts, incorporating direct impacts on water resources, secondary impacts on agriculture and other water interests, and indirect impacts through interstate migration of affected populations. Decision support tools are being integrated into scenario-based impact and adaptation assessments. For example, the Water Evaluation and Planning System model has been used to assess a community water system in British Columbia, Canada (Harma et al., 2012). Incorporation of stakeholder dialog processes within scenario construction (Parson, 2008) and Participatory Integrated Assessment (Salter et al., 2010) enables inclusion of local knowledge as part of scenario-based assessments.

2.4.2.2. Assessing Vulnerability, Risk, and Adaptive Capacity

The adaptation to climate change, disaster risk management, and resilience literatures all address the concept of vulnerability, defined as a susceptibility to loss or damage (Adger, 2006; Füssel, 2007), or the propensity or predisposition to be adversely affected (Glossary). Within IPCC AR4, Schneider et al. (2007) identified vulnerabilities that might be considered "key," and therefore potentially "dangerous" (see Glossary). Criteria denoting a key vulnerability include its magnitude and timing, persistence, and reversibility, and the likelihood and confidence that the contributing event(s) would occur (Sections 19.2.5, 19.6). Other criteria include the importance of a location or activity to society and society's exposure to potential loss and its capacity to adapt. Adaptive capacity has been defined as the ability to adjust, to take advantage of opportunities, or to cope with consequences (Adger et al., 2007; see also Glossary). However, adaptive capacity is context-specific, related to both availability of resources, capacity to learn, and governance measures (Gupta et al., 2010; see also Section 14.5). Actions that illustrate how adaptive capacity and climate resilience can be mutually reinforcing include disaster risk management (Sections 2.5.2, 15.3.2, 16.7.2) and "triple-win" interventions where adaptation, mitigation, and sustainable development goals are integrated so as to find climate-resilient pathways (Sections 20.3.3, 20.4.2).

The concept of an "adaptation deficit" (Burton and May, 2004) is applicable to cases such as Hurricane Katrina (Committee on New Orleans Regional Hurricane Protection Projects, 2009; Freudenberg et al., 2009; Box 2-1) or the 2003 European heat wave (Haines et al., 2006) where substantial vulnerability follows a climate event. An adaptation deficit represents a gap between an existing state of adaptation and an idealized state of adaptation where adverse impacts are avoided (Chapter 17; Glossary). The adaptation deficit has also been related to "residual impacts," which occur due to insufficient adaptation to current or future climate (IPCC, 2007a). Within developing countries, Narain et al. (2011) consider the adaptation deficit as being part of a larger "development deficit." Cardona et al. (2012) cite other "deficit" indicators, including a Disaster Deficit Index (extreme event impact combined with financial ability to cope), structural deficit (low income, high inequality, lack of access to resources, etc.), and a risk communication deficit. Maladaptation occurs where a short-term response inadvertently leads to an increase in future vulnerability (Glantz, 1988; Barnett and O'Neill, 2010; McEvoy and Wilder, 2012). Barriers unrelated to scientific knowledge can hamper effective decision making (Adger and Barnett, 2009; Berrang Ford et al., 2011). This may help to explain why some extreme events create surprising levels of damage within developed countries.

The assessment of potential future damages and loss requires approaches that link biophysical and socioeconomic futures. An example is the assessment of climate change effects on human health, including research-to-decision pathways, monitoring of social vulnerability indicators and health outcomes (English et al., 2009; Portier et al., 2010), and tools for enabling adaptive management (Hess et al., 2012). Examples of regional scale scenario-based vulnerability assessments are case studies for North Rhine-Westphalia in Germany (Holsten and Kropp, 2012) and agriculture in Mexico (Monterroso et al., 2012). An example of a larger scale study is a vulnerability assessment of ecosystem services for Europe, in which future adaptive capacity was based on indicators from the *Special Report on Emission Scenarios* (SRES) storylines (Metzger and Schröter, 2006). Difficulty in separating the relative influences of changing climate and development patterns hampers assessments of observed trends in property damage caused by atmospheric extreme events. Recent increases in economic losses may be due to changes in probabilities of extreme events, changes in human development patterns (more people in harm's way) without changes in climatic extremes, or a combination of both (Pielke, 1998; Mills, 2005; Munich Re Group, 2011). IPCC (2012) concluded that increasing exposure has been the major cause, but a role for climate change has not been excluded.

Development choices taken in the current or near term can potentially influence future vulnerability to projected climate change, hence interest in the study of emergent risks (Sections 19.3, 19.4). Interactions between development pathways, and climate change impacts and responses, could create situations with little or no precedent. Assessments based on gradual shifts in mean conditions could underestimate future risk and consequent damage, suggesting the need for process-based methodologies that focus on enhancing resilience (Jones et al., 2013; see also Sections 2.5.2, 20.2.3). An example of assessing this type of risk, and the costs and benefits of potential adaptation responses, is a resilience assessment framework for infrastructure networks (Vugrin et al., 2011; Turnquist and Vugrin, 2013).

2.4.3. Climate-Related Decisions in Practice

Implementation of adaptation actions, resilience strategies and capacity building can take place as stand-alone actions or be integrated into other management plans and strategies. Recent literature on potential climate change effects on natural resources, public health, and community planning and management is reviewed in Chapters 3 to 12. As the omplexity of management challenges increases due to climate change, development, and other pressures, a range of reflexive decision-making processes are emerging under the general topics of adaptive management, iterative risk management, and community-based adaptation (e.g., Section 5.5.4.1). However, there are few assessments of adaptation delivery and effectiveness (Section 15.6). Cross-sectoral integrated approaches such as Integrated Water Resources Management (IWRM), sustainable forestry management (SFM), and Integrated Coastal Zone Management (ICZM) are viewed as being more effective than stand-alone efforts (Section 16.5.1).

Adaptive approaches to water management can potentially address uncertainty due to climate change (Section 3.6.1) but there is a limited number of examples in practice (Section 3.6.4). Examples of recent strategies include an IWRM roadmap prepared for the state of Orissa, India (Jønch-Clausen, 2010) and seven cases in the USA (Bateman and Rancier, 2012), some of which are applying adaptive water management using a scenario-based experimental approach intending to align with IWRM and promote resilience. Adaptations in urban systems following integrated urban water management principles are becoming widespread (Section 8.3.3.4) and in rural systems are more advanced in developed countries and less so in developing countries, especially those within transboundary basins (Sections 9.4.3.2, 24.4.1.5, 24.4.2.5, 25.5.3, 26.3.3, 27.3.1.2, 27.3.2.2).

Adaptation in agriculture ranges from small adjustments made to current activities through to transformative adaptations across whole systems (Sections 7.5.1, 9.4.3.1, 22.4.5.7, 23.4.1, 24.4.4.5, 25.7.2, 26.5.4, 27.3.4.2). Diversified systems are more resilient with some diversification coming from off farm sources (Section 9.4.3.1). There are few unequivocal adaptations to climate, but the development of adaptive capacity is more widespread (Section 7.5.1.2). Adaptation in forestry has expanded since the AR4 (Section 9.4.3.3) and is aiming to develop toward SFM by focusing on biological diversity, productive and protective functions of forests, maintenance of their social and economic benefits, and governance (McDonald and Lane, 2004; Wijewardana, 2008; Montréal Process, 2009). Although SFM is still largely an abstract concept (Seppälä et al., 2009), managing climate change risks is seen as necessary for achieving its objectives (Montréal Process, 2009). Governments and companies are also considering assisted migration of forest species as an adaptation strategy (Pedlar et al., 2012) and payment for ecosystem services is becoming more common (Section 9.4.3.3). Sustainable Fisheries Management has long-term ecological and productivity goals (FAO, 2013) but climate change has generally not been included in strategic guidance for fisheries management (Brander, 2010). Ecosystem-based approaches to management (e.g., Zhou et al., 2010) and transformative approaches will be required (Sections 7.5.1.1.2, 9.4.3.4). Sustainable livelihoods approaches are also being applied for populations dependent on marine resources (Sections 9.4.3.4, 30.6.2.1; Table 30-2).

National Adaptation Programmes of Action (NAPA) for least-developed countries (LDCs) are designed to be flexible, action-oriented, and country-driven (UNFCCC, 2009). Key preparatory steps include the synthesis of available information on vulnerability and impacts via extensive public participation (see Chapter 14). The NAPA process has assisted LDCs to assess climate sensitive sectors and prioritize projects to address the most urgent adaptation issues (Lal et al., 2012; UNFCCC, 2012). Integrating NAPAs with other socioeconomic programs can help develop resilience. However, although many countries have linked their NAPAs with development programs, Hardee and Mutunga (2010) argue that they have had limited success in aligning the NAPA priorities with existing national priorities such as population growth. To this end, scaling up and institutionalization of the NAPA process has commenced. Under the Cancun Adaptation Framework, a process was established that enables LDCs to formulate and implement National Adaptation Plans (NAPs) building upon the NAPA experience (UNFCCC, 2013). The NAP's main objectives are to identify vulnerabilities and medium- and long-term adaptation needs, and to develop and implement strategies and programs to address those needs and also to mainstream climate change risks. The NAPs are also an opportunity to align with other global initiatives such as the Millennium Development Goals and Hyogo Framework for Action.

Many developed countries are developing adaptation strategy documents at different scales of governance (European Environmental Agency, 2013). Biesbroek et al. (2010) analysed National Adaptation Strategies (NAS) of nine European nations, examining their decision making aspects and finding both "top-down" and "bottom-up" (delegation of authorities to local governments) approaches. Dissemination of information on weather, climate, impacts, vulnerability, and scenarios was found to be a critical element for adaptation decision making.

Climate risk is being increasingly factored into existing decision-making processes (Section 15.2.1). For example, learning from the 2003 heat waves that killed some 35,000 people across Europe, many European countries have implemented health-watch warning systems (Alcamo et al., 2007; WHO, 2008). Vietnam has initiated large-scale mangrove restoration and rehabilitation programs with the support of international institutions to protect coastal settlements and aquaculture industry (World Resources Institute et al., 2011). The Tsho Rolpa glacier lake in Nepal was at the risk of outburst due to glacial melt (Adger et al., 2007) so the Government of Nepal introduced both short- and long-term measures to prevent the outburst flood event (World Resources Institute et al., 2011). In many ways, local government is at the coal face of adaptation decision making (Pelling et al., 2008; Measham et al., 2011; Roberts et al., 2012). Municipal governments are incorporating climate change adaptation planning within municipal planning instruments, including energy and water system design, disaster risk reduction, and sustainability plans (Ford and Berrang-Ford, 2011; Rosenzweig et al., 2011). In human health, two main areas of benefit are occurring through improvements in current health patterns being exacerbated by changing climate and in reducing pollutants associated with co-pollutants of GHG emissions (Sections 11.7, 11.9). Climate is being increasingly recognized as a component of human conflict and insecurity, so is becoming a factor in governance arrangements affecting security and peace building programs (Section 12.5).

Details of adaptation planning within urban and rural settlements are addressed in Chapters 8 and 9, respectively. In urban settlements, adaptations are occurring in areas of energy, water, transport, housing, and green infrastructure (Section 8.3.3) but opportunities for broader integration into planning and the urban economy are largely being missed (Section 8.4). The overall status of adaptation implementation is assessed in Chapter 15. Although there is a rapidly growing list of adaptation plans being generated at multiple scales, an evaluation of adaptation plans from Australia, UK, and the USA suggests they are under-developed (Berrang Ford et al., 2011). These plans reflect a preference for capacity building over delivery of specific vulnerability-reduction measures, indicating that current adaptation planning is still informal and ad hoc (Preston et al., 2011; Bierbaum et al., 2013).

Frequently Asked Questions

FAQ 2.3 | Is climate change decision making different from other kinds of decision making?

Climate-related decisions have similarities and differences with decisions concerning other long-term, high-consequence issues. Commonalities include the usefulness of a broad risk framework and the need to consider uncertain projections of various biophysical and socioeconomic conditions. However, climate change includes longer time horizons and affects a broader range of human and Earth systems as compared to many other sources of risk. Climate change impact, adaptation, and vulnerability assessments offer a specific platform for exploring long-term future scenarios in which climate change is considered along with other projected changes of relevance to long-term planning.

In many situations, climate change may lead to non-marginal and irreversible outcomes, which pose challenges to conventional tools of economic and environmental policy. In addition, the realization that future climate may differ significantly from previous experience is still relatively new for many fields of practice (e.g., food production, natural resources management, natural hazards management, insurance, public health services, and urban planning).

Capacity barriers have hampered the transition from planning to implementation, so only a small number of jurisdictions have been successful at implementing adaptation measures (Section 15.2). However, there has been growth in community-based adaptation initiatives (Baer and Risbey, 2009; Rudiak-Gould, 2011; Sections 15.1, 15.2, 15.5, 15.6).

Various enabling factors for implementation have been identified in stakeholder engagement processes. Such factors include access to resources and sharing observations, language specific information, and ICT tools (e.g., wireless sensor networks, geographic information systems and web-based tools) that increase local awareness, allowing for good public understanding of stresses, risks, and trade-offs (Section 15.4.2). These factors allow new strategies to be explored, evaluated, and implemented (Shepherd et al., 2006; Hewitt et al., 2013). Enabling factors also include customized impact and vulnerability assessments for communities of interest and local practitioners who would serve as champions for adaptation planning, and the existence of local social influences/networks and capacity that enable long-term strategic planning and mainstreaming (Gardner et al., 2009; Cohen, 2010). These factors are further discussed in Chapters 15 and 16. Local government officials often lack training on climate change adaptation and require capacity to be built in a number of areas. To assist this process, guidebooks have been produced, framing the process of adaptation planning as both a team-building and project management exercise, activities that are already part of usual practice (Snover et al., 2007; Bizikova et al., 2008; ICLEI Oceania, 2008; CARE International in Vietnam, 2009; Ayers et al., 2012). Practitioner engagement in decision "games" can offer another training resource (Black et al., 2012).

2.5. Linking Adaptation with Mitigation and Sustainable Development

2.5.1. Assessing Synergies and Trade-offs with Mitigation

Capacities to adapt to and mitigate climate change are broadly similar. Opportunities for synergies are particularly relevant for the agriculture, forestry, urban infrastructure, energy, and water sectors (Chapters 3, 4, 7 to 10). The IPCC AR4 (Klein et al., 2007) concluded that a lack of information made it difficult to assess these synergies. Assessing the synergies and trade-offs that face both adaptation and mitigation is an important goal of the new IPCC scenario process (Kriegler et al., 2012; O'Neill et al., 2014). These synergies and trade-offs between adaptation and mitigation are illustrated in Figure 2-4. The negatives associated with "adaptive emissions" or "new vulnerabilities" arising from mitigation do not necessarily mean that such measures should not be contemplated, but they do need to be assessed within a larger portfolio of actions where losses and gains have been sufficiently well quantified (Section 19.7). Limits of adaptation emphasize the different reach of adaptation and mitigation in managing climate risks (Sections 16.6, 19.7.5).

Mitigation can affect, for example, water resources (Section 3.7.2.1), terrestrial and freshwater ecosystems (Sections 4.4.4, 19.3.2.2), agriculture (Sections 19.3.2.2, 19.4.1), and livelihoods and poverty (Section 13.3.1), and will in turn be affected by changes in water resources (Section 3.7.3.2) and terrestrial ecosystems (Sections 4.3.3.1, 4.2.4.1). Adaptation actions for agriculture generally tend to reduce emissions (Section 7.5.1.4). Potential losses of human security associated with climate policy are discussed in Sections 12.5.2 and 19.4.2.2. Recent literature on potential interactions between mitigation and adaptation is reviewed in Sections 16.4.3, 19.7.1, 19.7.2, 19.7.3, 19.7.4, and 19.7.5. Chapter 20 discusses the relationship between adaptation, mitigation, and sustainable development including sustainable risk management (Section 20.3.3).

2.5.2. Linkage with Sustainable Development: Resilience

The idea that climate change response and sustainable development should be integrated within a more holistic decision framework was assessed in IPCC AR4 (Robinson et al., 2006; Klein et al., 2007; Yohe et al., 2007). Practical aspects of this integration are being tested as decision makers endeavor to incorporate adaptation measures within official long-term development plans (Section 15.3.3). A typical example is the engagement of researchers and practitioners (planners, engineers, water managers, etc.) in scenario-based exercises to build local capacity to plan for a wide range of climate outcomes (Bizikova et al., 2010). Development can yield adaptation co-benefits if climate change is factored into its design (Sections 17.2.7.2, 20.3, 20.4).

Resilience is the capacity to change in order to maintain the same identity (see Glossary) and can be assessed through participatory research (Tyler and Moench, 2012) or through system modelling. Chapter 20 examines climate-resilient pathways, which are development trajectories of combined mitigation and adaptation to realize the goal of sustainable development while meeting the goals of the UNFCCC (Box 20-1). An example of resilience assessment at the landscape scale is in the Arctic, where local sources of important productivity and biodiversity are being mapped and their future capacity in supporting larger ecoregions under climate change is being assessed (Christie and Sommerkorn, 2012). An industry example covers the resilience analysis of supply chains, specifically petrochemical supply chains exposed to a hurricane in the southeastern USA (Vugrin et al., 2011). For urban areas, Leichenko (2011) categorize four types of urban resilience studies: (1) urban ecological resilience, (2) urban hazards and disaster risk reduction, (3) resilience of urban and regional economies, and (4) urban governance and institutions. Boyd et al. (2008) promote resilience as a way of guiding future urbanization that would be better "climatized." The Asian Cities Climate Change Resilience Network is applying a resilience planning framework, with attention given to the role of agents and institutions (Tyler and Moench, 2012).

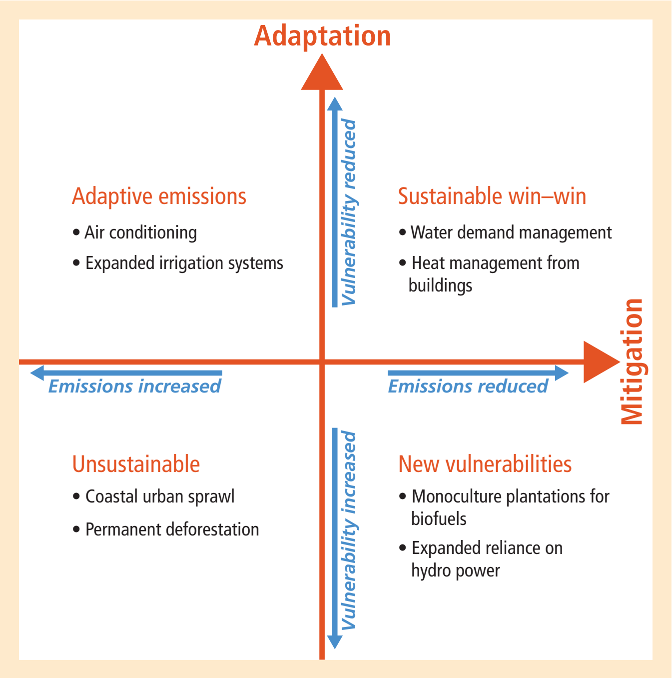


Figure 2-4 | Examples of adaptation (A): mitigation (M) trade-offs and synergies (adapted from Cohen and Waddell, 2009). The upper right quadrant (sustainable win–win) illustrates synergies in which actions enable the achievement of both adaptation and mitigation goals. The lower left quadrant (unsustainable) shows the opposite condition. The upper left (adaptive emissions) and lower right (new vulnerabilities) quadrants illustrate trade-offs that can result from actions within particular local-regional circumstances.

Adaptive capacity is seen as an important component of resilience on a range of scales (Sections 2.1.1, 2.2.3, 2.3.4, 2.4.2, 20.3). Local cases, such as King County (Seattle) USA, illustrate the importance of researcher-practitioner collaboration for knowledge exchange (Snover et al., 2007) and iterative and reflexive processes that enable local ownership, and adjustment to new information and evaluation of actions taken (Saavedra and Budd, 2009). However, in regions with high and chronic poverty, coupled with low awareness of global change drivers, adaptation as a process is not well understood and tools that enable anticipatory learning are lacking (Tschakert and Dietrich, 2010).

The normative concept of sustainable adaptation has been proposed to manage adaptation's unintended consequences (Eriksen et al., 2011). It considers effects on social justice and environmental integrity, challenging current (unsustainable) development paths rather than seeking adjustments within them. This concept recognizes the role of multiple stressors in vulnerability, the importance of values in affecting adaptation outcomes (Section 2.2.1), and potential feedbacks between local and global processes. Little is known about the long-term effects of adaptation on livelihoods and poverty (Section 13.3.2) although focusing on poverty alleviation as part of adaptation is thought to build capacity (Sections 13.4.1, 13.4.2).

The Hyogo Framework for Action on disaster risk reduction considers climate change as an underlying risk factor, and promotes the integration of risk reduction and climate change adaptation (UNISDR, 2007, 2011; see also Section 15.3.2). Social development is being integrated with disaster risk management in order to enhance adaptive capacity and address the structural causes of poverty, vulnerability, and exposure. In small island states, this integration is being enabled through focused institutional coordination, greater stakeholder engagement, and promotion of community-based adaptation and resilience-building projects (UNISDR and UNDP, 2012). Similar initiatives are underway in urban areas (UNISDR, 2012; see also Sections 15.3.2, 15.3.3, 15.5; Chapter 24; Box CC-TC).

Resilience is also being explored as an outcome of social contracts that underpin governance. O'Brien et al. (2009) use examples from Norway, New Zealand, and Canada to illustrate how resilience thinking on climate does not easily fit into existing social contracts, and that new types of arrangements may better serve the goals of resilience and sustainable development within the context of climate change. Chapter 20 describes climate-resilient development pathways as being an explicit objective of long-term planning and decision making and considers the need for transformational adaptation aiming to achieve sustainable development (Sections 20.5).

2.5.3. Transformation: How Do We Make Decisions Involving Transformation?

Much of the existing adaptation literature examines gradual adjustment or accommodation to change. But a growing literature highlights the importance of transformative adaptation (Sections 14.3.5, 16.4.2), both in the context of a world where global temperature raise above 2°C (Kates et al., 2012; PIK, 2012) and in the context of climate-resilient pathways that manage risk through combinations of adaptation and mitigation (Section 20.5).

In concluding this chapter, we therefore reflect on some emerging, though still sparse, literature that examines such transformational adaptation, how it differs from incremental adaptation (O'Brien, 2012; Park et al., 2012), and how it might occur in specific sectors and systems (Rickards and Howden, 2012). This early literature suggests that many themes raised in this chapter may prove important to transformational adaptation, including iterative risk management with a broad view of risk, adaptive management, robustness and resilience, and deliberation (McGray et al., 2007; Leary et al., 2008; Hallegatte, 2009; Tschakert and Dietrich, 2010; Hallegatte et al., 2011; Stafford Smith et al., 2011). For instance, Irvin and Stansbury (2004) identify situations where participatory processes may be most effective for bringing about positive social and environmental change. Recently, Park et al. (2012) have proposed the Adaptation Action Cycles concept as a means to delineate incremental and transformative adaptation and the role of learning in the decision-making process. Similar to the learning process called "triple-loop"—which considers a situation, its drivers, plus the underlying frames and values that provide the situation context (Argyris and Schön, 1978; Peschl, 2007; Hargrove, 2008)—transformational adaptation may involve decision makers questioning deep underlying principles (Flood and Romm, 1996; Pelling et al., 2008) and seeking changes in institutions, such as legal and regulatory structures underlying environmental and natural resource management (Craig, 2010 ; Ruhl, 2010a), as well as in cultural values (O'Brien, 2012; O'Brien et al., 2013).

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3 Freshwater Resources

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3

Executive Summary

Key Risks at the Global Scale

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas (GHG) concentrations (*robust evidence*, *high agreement*). {3.4, 3.5} Modeling studies since AR4, with large but better quantified uncertainties, have demonstrated clear differences between global futures with higher emissions, which have stronger adverse impacts, and those with lower emissions, which cause less damage and cost less to adapt to. {Table 3-2} For each degree of global warming, approximately 7% of the global population is projected to be exposed to a decrease of renewable water resources of at least 20% (multi-model mean). By the end of the 21st century, the number of people exposed annually to the equivalent of a 20th-century 100-year river flood is projected to be three times greater for very high emissions (Representative Concentration Pathway 8.5 (RCP8.5)) than for very low emissions (RCP2.6) (multi-model mean) for the fixed population distribution at the level in the year 2005. {Table 3-2, 3.4.8}

Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*robust evidence*, *high agreement*). {3.4, 3.5} This will intensify competition for water among agriculture, ecosystems, settlements, industry, and energy production, affecting regional water, energy, and food security (*limited evidence*, *medium* to *high agreement*). {3.5.1, 3.5.2, Box CC-WE} In contrast, water resources are projected to increase at high latitudes. Proportional changes are typically one to three times greater for runoff than for precipitation. The effects on water resources and irrigation requirements of changes in vegetation due to increasing GHG concentrations and climate change remain uncertain. {Box CC-VW}

3

So far there are no widespread observations of changes in flood magnitude and frequency due to anthropogenic climate change, but projections imply variations in the frequency of floods (*limited evidence*, *medium agreement*). Flood hazards are projected to increase in parts of South, Southeast, and Northeast Asia; tropical Africa; and South America (*limited evidence*, *medium agreement*). Since the mid-20th century, socioeconomic losses from flooding have increased mainly due to greater exposure and vulnerability (*high confidence*). Global flood risk will increase in the future partly due to climate change (*limited evidence*, *medium agreement*). {3.2.7, 3.4.8}

Climate change is *likely* to increase the frequency of meteorological droughts (less rainfall) and agricultural droughts (less soil moisture) in presently dry regions by the end of the 21st century under the RCP8.5 scenario (*medium confidence*). {WGI AR5 Chapter 12} This is *likely* to increase the frequency of short hydrological droughts (less surface water and groundwater) in these regions (*medium evidence*, *medium agreement*). {3.4.8} Projected changes in the frequency of droughts longer than 12 months are more uncertain, because these depend on accumulated precipitation over long periods. There is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand. {3.5.1}

Climate change negatively impacts freshwater ecosystems by changing streamflow and water quality (*medium evidence*, *high agreement*). Quantitative responses are known in only a few cases. Except in areas with intensive irrigation, the streamflow-mediated ecological impacts of climate change are expected to be stronger than historical impacts owing to anthropogenic alteration of flow regimes by water withdrawals and the construction of reservoirs. {Box CC-RF, 3.5.2.4}

Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (*medium evidence*, *high agreement*). The sources of the risks are increased temperature, increases in sediment, nutrient and pollutant loadings due to heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods. {3.2.5, Figure 3-2, 3.4.6, 3.5.2.3}

In regions with snowfall, climate change has altered observed streamflow seasonality, and increasing alterations due to climate change are projected (*robust evidence*, *high agreement*). {Table 3-1, 3.2.3, 3.2.7, 3.4.5, 3.4.6, 26.2.2} Except in very cold regions, warming in the last decades has reduced the spring maximum snow depth and brought forward the spring maximum of snowmelt discharge; smaller snowmelt floods, increased winter flows, and reduced summer low flows have all been observed. River ice in Arctic rivers has been observed to break up earlier. {3.2.3, 28.2.1.1}

Because nearly all glaciers are too large for equilibrium with the present climate, there is a committed water resources change during much of the 21st century, and changes beyond the committed change are expected due to continued warming; in glacier-fed rivers, total meltwater yields from stored glacier ice will increase in many regions during the next decades but decrease thereafter (*robust evidence*, *high agreement*). Continued loss of glacier ice implies a shift of peak discharge from summer to spring, except in monsoonal catchments, and possibly a reduction of summer flows in the downstream parts of glacierized catchments. {3.4.3}

There is little or no observational evidence yet that soil erosion and sediment loads have been altered significantly due to changing climate (*limited evidence*, *medium agreement*). However, increases in heavy rainfall and temperature are projected to change soil erosion and sediment yield, although the extent of these changes is highly uncertain and depends on rainfall seasonality, land cover, and soil management practices. {3.2.6, 3.4.7}

Adaptation, Mitigation, and Sustainable Development

Of the global cost of water sector adaptation, most is necessary in developing countries where there are many opportunities for anticipatory adaptation (*medium evidence*, *high agreement*). There is limited published information on the water sector costs of adaptation at the local level. {3.6.1, 3.6.3}

An adaptive approach to water management can address uncertainty due to climate change (*limited evidence*, *high agreement*). Adaptive techniques include scenario planning, experimental approaches that involve learning from experience, and the development of flexible and low-regret solutions that are resilient to uncertainty. Barriers to progress include lack of human and institutional capacity, financial resources, awareness, and communication. {3.6.1, 3.6.2, 3.6.4}

Reliability of water supply, which is expected to suffer from increased variability of surface water availability, may be enhanced by increased groundwater abstractions (*limited evidence*, *high agreement*). This adaptation to climate change is limited in regions where renewable groundwater resources decrease due to climate change. {3.4.5, 3.4.8, 3.5.1}

Some measures to reduce GHG emissions imply risks for freshwater systems (*medium evidence*, *high agreement*). If irrigated, bioenergy crops make water demands that other mitigation measures do not. Hydropower has negative impacts on freshwater ecosystems, which can be reduced by appropriate management. Carbon capture and storage can decrease groundwater quality. In some regions, afforestation can reduce renewable water resources but also flood risk and soil erosion. {3.7.2.1, Box CC-WE}

3.1. Introduction

Changes in the hydrological cycle due to climate change can lead to diverse impacts and risks, and they are conditioned by and interact with non-climatic drivers of change and water management responses (Figure 3-1). Water is the agent that delivers many of the impacts of climate change to society, for example, to the energy, agriculture, and transport sectors. Even though water moves through the hydrological cycle, it is a locally variable resource, and vulnerabilities to water-related hazards such as floods and droughts differ between regions. Anthropogenic climate change is one of many stressors of water resources. Non-climatic drivers such as population increase, economic development, urbanization, and land use or natural geomorphic changes also challenge the sustainability of resources by decreasing water supply or increasing demand. In this context, adaptation to climate change in the water sector can contribute to improving the availability of water.

The key messages with *high* or *very high confidence* from the Working Group II Fourth Assessment Report (AR4; IPCC, 2007) in respect to freshwater resources were:

- The observed and projected impacts of climate change on freshwater systems and their management are due mainly to increases in temperature and sea level, local changes of precipitation, and changes in the variability of those quantities.
- Semiarid and arid areas are particularly exposed.
- Warmer water, more intense precipitation, and longer periods of low flow reduce water quality, with impacts on ecosystems, human health, and reliability and operating costs of water services.
- Climate change affects water management infrastructure and practice.
- Adaptation and risk management practices have been developed for the water sector in some countries and regions.
- The negative impacts of climate change on freshwater systems outweigh its benefits.

This chapter assesses hydrological changes due to climate change, based mainly on research published since AR4. Current gaps in research and data are summarized in Section 3.8. For further information on observed trends in the water cycle, please see Chapter 2 of the Working Group I (WGI) contribution to this assessment. See WGI AR5 Chapter 4 for freshwater in cold regions and WGI AR5 Chapters 10 for detection and attribution, 11 for near-term projections, and 12 for long-term projections of climate change. In this Working Group II contribution, impacts on aquatic ecosystems are discussed in Chapter 4 (see also Section 3.5.2.4). Chapter 7 describes the impacts of climate change on food production (see also Section 3.5.2.1 for the impact of hydrological changes on the agricultural sector). The health effects of changes in water quality and quantity are covered in Chapter 11, and regional vulnerabilities related to freshwater in Chapters 21 to 30. Sections 3.2.7, 3.4.8, and 3.6.3 discuss impact and adaptation costs related to water resources; these costs are assessed more broadly in Chapter 10.

3.2. Observed Hydrological Changes Due to Climate Change

3.2.1. Detection and Attribution

A documented hydrological change is not necessarily due to anthropogenic climate change. Detection entails showing, usually statistically, that part

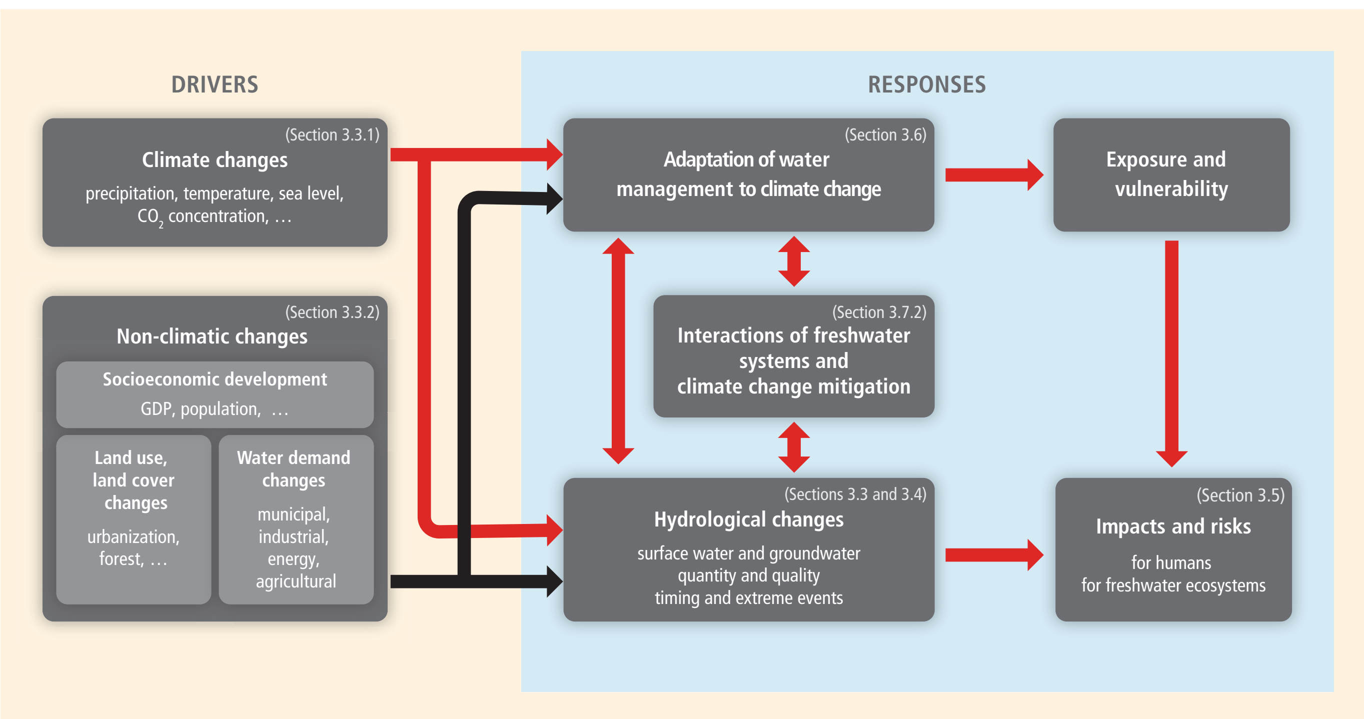
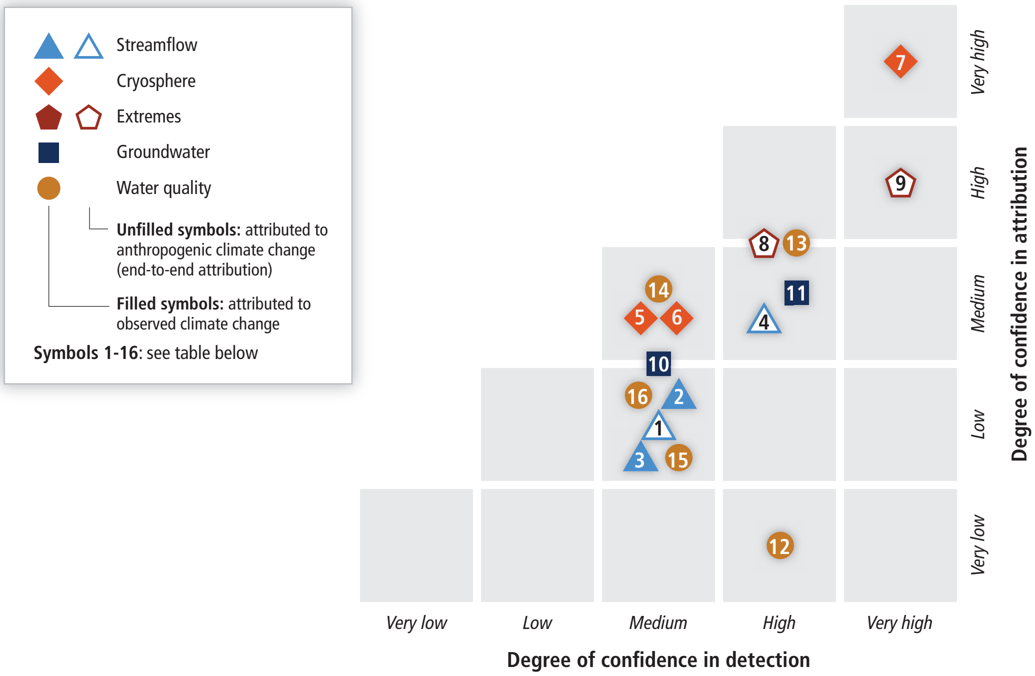


Figure 3-1 | Framework (boxes) and linkages (arrows) for considering impacts of climatic and social changes on freshwater systems, and consequent impacts on and risks for humans and freshwater ecosystems. Both climatic (Section 3.3.1) and non-climatic (Section 3.3.2) drivers have changed natural freshwater systems (Section 3.2) and are expected to continue to do so (Section 3.4). They also stimulate adaptive measures (Section 3.6). Hydrological and water management changes interact with each other and with measures to mitigate climate change (Section 3.7.2). Adaptive measures influence the exposure and vulnerability of human beings and ecosystems to water-related risks (Section 3.5).

Table 3-1 | Selected examples, mainly from Section 3.2, of the observation, detection, and attribution of impacts of climate change on freshwater resources. Observed hydrological changes are attributed here to their climatic drivers, not all of which are necessarily anthropogenic.



	Observed change	Attributed to	Reference
1	Changed runoff (global, 1960–1994)	Mainly climatic change, and to a lesser degree CO_2 increase and land use change	Gerten et al. (2008); Piao et al. (2007); Alkama et al. (2011)
2	Reduced runoff (Yellow River, China)	Increased temperature; only 35% of reduction attributable to human withdrawals	Piao et al. (2010)
3	Earlier annual peak discharge (Russian Arctic, 1960–2001)	Increased temperature and earlier spring thaw	Shiklomanov et al. (2007)
4	Earlier annual peak discharge (Columbia River, western USA, 1950–1999)	Anthropogenic warming	Hidalgo et al. (2009)
5	Glacier meltwater yield greater in 1910–1940 than in 1980–2000 (European Alps)	Glacier shrinkage forced by comparable warming rates in the two periods	Collins (2008)
6	Decreased dry-season discharge (Peru, 1950s–1990s)	Decreased glacier extent in the absence of a clear trend in precipitation	Baraer et al. (2012)
7	Disappearance of Chacaltaya Glacier, Bolivia (2009)	Ascent of freezing isotherm at 50 meters per decade, 1980s–2000s	Rosenzweig et al. (2007)
8	More intense extremes of precipitation (northern tropics and mid-latitudes, 1951–1999)	Anthropogenic greenhouse gas emissions	Min et al. (2011)
9	Fraction of risk of flooding (England and Wales, autumn 2000)	Extreme precipitation attributable to anthropogenic greenhouse radiation	Pall et al. (2011)
10	Decreased recharge of karst aquifers (Spain, 20th century)	Decreased precipitation, and possibly increased temperature; multiple confounding factors	Aguilera and Murillo (2009)
11	Decreased groundwater recharge (Kashmir, 1985–2005)	Decreased winter precipitation	Jeelani (2008)
12	Increased dissolved organic carbon in upland lakes (UK, 1988–2003)	Increased temperature and precipitation; multiple confounding factors	Evans et al. (2005)
13	Increased anoxia in a reservoir, moderated during ENSO (El Niño-Southern Oscillation) episodes (Spain, 1964–1991 and 1994–2007)	Decreased runoff due to decreased precipitation and increased evaporative demand	Marcé et al. (2010)
14	Variable fecal pollution in a saltwater wetland (California, 1969–2000)	Variable storm runoff; 70% of coliform variability attributable to variable precipitation	Pednekar et al. (2005)
15	Nutrient flushing from swamps, reservoirs (North Carolina, 1978–2003)	Hurricanes	Paerl et al. (2006)
16	Increased lake nutrient content (Victoria, Australia, 1984–2000)	Increased air and water temperature	Tibby and Tiller (2007)

of the documented change is not due to natural variability of the water cycle (Chapter 18; WGI AR5 Chapter 10). For robust attribution to climatic change, all the drivers of the hydrological change must be identified, with confidence levels assigned to their contributions. Human contributions such as water withdrawals, land use change, and pollution mean that this is usually difficult. Nevertheless, many hydrological impacts can be attributed confidently to their climatic drivers (Table 3-1). End-to-end attribution, from human climate-altering activities to impacts on freshwater resources, is not attempted in most studies, because it requires experiments with climate models in which the external natural and anthropogenic forcing is "switched off." However, climate models do not currently simulate the water cycle at fine enough resolution for attribution of most catchment-scale hydrological impacts to anthropogenic climate change. Until climate models and impact models become better integrated, it is necessary to rely heavily on multistep attribution, in which hydrological changes are shown to result from climatic changes that may in turn result partly from human activities.

Extreme hydrological events, such as floods, prompt speculation about whether they are "caused" by climate change. Climate change can indeed alter the probability of a particular event. However, to estimate the alteration reliably it is necessary to quantify uncertainties due to natural variability in the changed and the unchanged climates, and also—because of the need for model simulations—uncertainties due to limited ability to simulate the climate.

The probability or risk of the extreme event can be measured by recording the fraction of events beyond some threshold magnitude. Call this fraction r_{ctrl} in the simulated actual climate and r_{expt} in the simulated climate in which there is no anthropogenic forcing, and suppose there are many paired instances of r_{ctrl} and r_{expt}, with the ratio of risks in each pair given by $F = r_{expt} / r_{ctrl}$. The distribution of risk ratios F describes the likelihood that the climate change has altered the risk. Several thousand pairs of such simulations were run to estimate the risk ratio for the floods in England and Wales in autumn 2000 (Pall et al., 2011). Each pair started from a unique initial state that differed slightly from a common reference state, and was obtained with a seasonal forecast model driven by patterns of attributable warming found beforehand from four climate-model simulations of the 20th century. The forecast model was coupled to a model of basin-scale runoff and channel-scale hydraulics. It is not probable that such exercises will become routine for assessing single-event risks in, for example, the insurance industry, because the necessary amount of computation is so formidable. Nevertheless, the result was compelling: in each of the four sets of simulation pairs, the risk increased greatly on average in the runs forced by anthropogenic greenhouse radiation. In aggregate, the most probable amount of increase was two- to threefold, and at most a few percent of the simulation pairs suggested that anthropogenic forcing actually decreased the risk. This summary is worded carefully: the thousands of simulation pairs were needed for quantifying the uncertainties, which led unavoidably to a spread of likelihoods and thus to statements about uncertainty about risk that are themselves uncertain.

3.2.2. Precipitation, Evapotranspiration, Soil Moisture, Permafrost, and Glaciers

Global trends in precipitation from several different datasets during 1901–2005 are statistically insignificant (Bates et al., 2008; WGI AR5 Chapter 2). According to regional observations, most droughts and extreme rainfall events of the 1990s and 2000s have been the worst since the 1950s (Arndt et al., 2010), and certain trends in total and extreme precipitation amounts are observed (WGI AR5 Chapter 2). Most regional changes in precipitation are attributed either to internal variability of the atmospheric circulation or to global warming (Lambert et al., 2004; Stott et al., 2010). It was estimated that the 20th century anthropogenic forcing contributed significantly to observed changes in global and regional precipitation (Zhang et al., 2007). Changes in snowfall amounts are indeterminate, as for precipitation; however, consistent with observed warming, shorter snowfall seasons are observed over most of the Northern Hemisphere, with snowmelt seasons starting earlier (Takala et al., 2009). In Norway, increased temperature at lower altitudes has reduced the snow water equivalent (Skaugen et al., 2012).

Steady decreases since the 1960s of global and regional actual evapotranspiration and pan evaporation have been attributed to changes in precipitation, diurnal temperature range, aerosol concentration, (net) solar radiation, vapor pressure deficit, and wind speed (Fu et al., 2009; McVicar et al., 2010; Miralles et al., 2011; Wang A. et al., 2011). Regional downward and upward trends in soil moisture content have been calculated for China from 1950 to 2006, where longer, more severe, and more frequent soil moisture droughts have been experienced over 37% of the land area (Wang A. et al., 2011). This is supported by detected increases since the 1960s in dry days and a prolongation of dry periods (Gemmer et al., 2011; Fischer et al., 2013), and can be attributed to increases in warm days and warm periods (Fischer et al., 2011).

Decreases in the extent of permafrost and increases in its average temperature are widely observed, for example, in some regions of the Arctic and Eurasia (WGI AR5 Chapter 4) and the Andes (Rabassa, 2009). Active layer depth and permafrost degradation are closely dependent on soil ice content. In steep terrain, slope stability is highly affected by changes in permafrost (Harris et al., 2009). The release of greenhouse gases (GHGs) due to permafrost degradation can have unprecedented impacts on the climate, but these processes are not yet well represented in global climate models (Grosse et al., 2011). In most parts of the world glaciers are losing mass (Gardner et al., 2013). For example, almost all glaciers in the tropical Andes have been shrinking rapidly since the 1980s (Rabassa, 2009; Rabatel et al., 2013); similarly, Himalayan glaciers are losing mass at present (Bolch et al., 2012).

3.2.3. Streamflow

Detected trends in streamflow are generally consistent with observed regional changes in precipitation and temperature since the 1950s. In Europe, streamflow (1962–2004) decreased in the south and east and generally increased elsewhere (Stahl et al., 2010, 2012), particularly in northern latitudes (Wilson et al., 2010). In North America (1951–2002), increases were observed in the Mississippi basin and decreases in the U.S. Pacific Northwest and southern Atlantic–Gulf regions (Kalra et al., 2008). In China, a decrease in streamflow in the Yellow River (1960–2000) is consistent with a reduction of 12% in summer and autumn precipitation, whereas the Yangtze River shows a small increase in annual streamflow driven by an increase in monsoon rains (Piao et al., 2010; see Table 3-1). These and other streamflow trends must be interpreted with caution (Jones, 2011) because of confounding factors such as land use changes (Zhang and Schilling, 2006), irrigation (Kustu et al., 2010), and urbanization (Wang and Cai, 2010).

In a global analysis of simulated streamflows (1948–2004), about one-third of the top 200 rivers (including the Congo, Mississippi, Yenisei, Paraná, Ganges, Columbia, Uruguay, and Niger) showed significant trends in discharge; 45 recorded decreases and only 19 recorded increases (Dai et al., 2009). Decreasing trends in low and mid-latitudes are consistent with recent drying and warming in West Africa, southern Europe, south and east Asia, eastern Australia, western Canada and the USA, and northern South America (Dai, 2013). The contribution to observed streamflow changes due to decreased stomatal opening of many plant species at higher carbon dioxide (CO_2) concentration remains disputed (Box CC-VW).

In regions with seasonal snow storage, warming since the 1970s has led to earlier spring discharge maxima (*robust evidence*, *high agreement*) and has increased winter flows because more winter precipitation falls as rain instead of snow (Clow, 2010; Korhonen and Kuusisto, 2010; Tan et al., 2011). There is *robust evidence* of earlier breakup of river ice in Arctic rivers (de Rham et al., 2008; Smith, 2000). Where streamflow is lower in summer, decrease in snow storage has exacerbated summer dryness (Cayan et al., 2001; Knowles et al., 2006).

3.2.4. Groundwater

Attribution of observed changes in groundwater level, storage, or discharge to climatic changes is difficult owing to additional influences of land use changes and groundwater abstractions (Stoll et al., 2011). Observed trends are largely attributable to these additional influences. The extent to which groundwater abstractions have already been affected by climate change is not known. Both detection of changes in groundwater systems and attribution of those changes to climatic changes are rare owing to a lack of appropriate observation wells and a small number of studies. Observed decreases of the discharge of groundwater-fed springs in Kashmir (India) since the 1980s were attributed to observed precipitation decreases (Jeelani, 2008; Table 3-1). A model-based assessment of observed decreases of groundwater levels in four overexploited karst aquifers in Spain led to the conclusion that groundwater recharge not only decreased strongly during the 20th century due to the decreasing precipitation but also that groundwater recharge as a fraction of observed precipitation declined progressively, possibly indicating an increase in evapotranspiration (Aguilera and Murillo, 2009; Table 3-1).

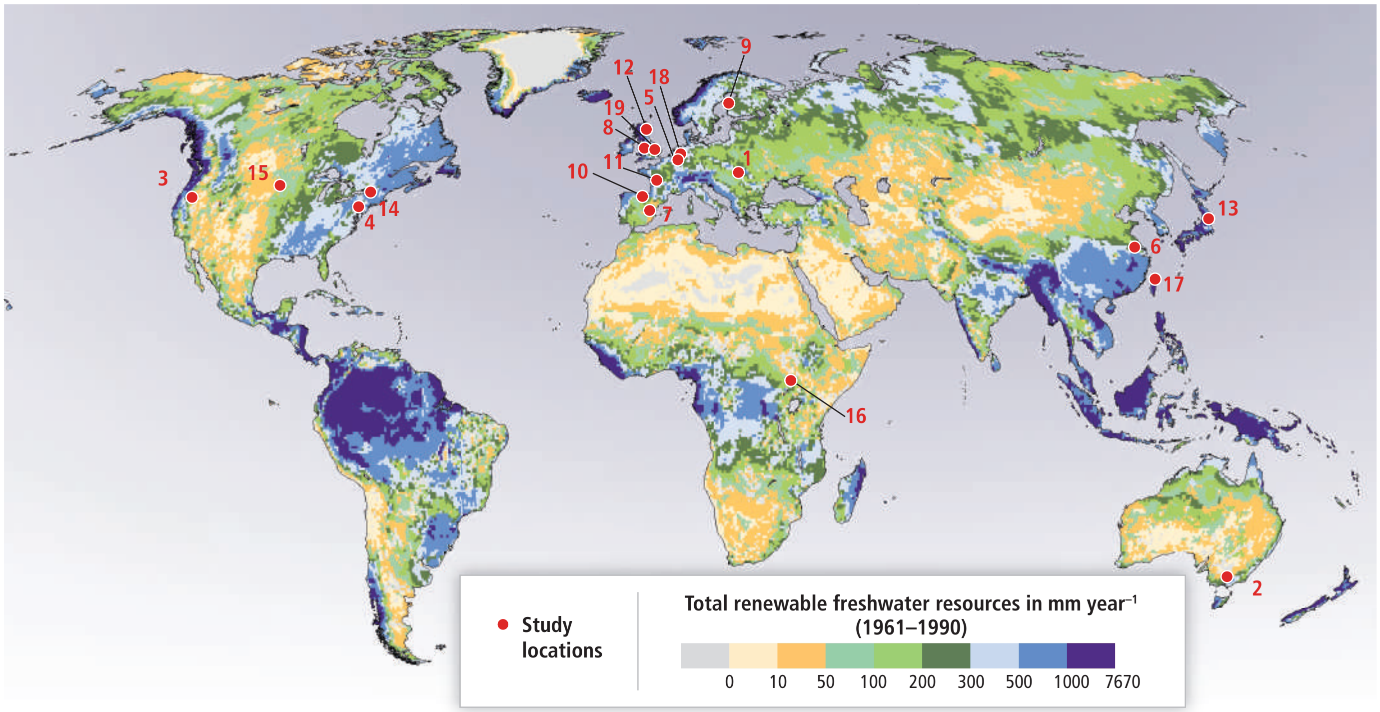
3.2.5. Water Quality

Most observed changes of water quality due to climate change (Table 3-1; Figure 3-2) are known from isolated studies, mostly of rivers or lakes in high-income countries, of a small number of variables. In addition, even though some studies extend over as many as 80 years, most are short term. For lakes and reservoirs, the most frequently reported change is more intense eutrophication and algal blooms at higher temperatures, or shorter hydraulic retention times and higher nutrient loads resulting from increased storm runoff (*medium* to *robust evidence*, *high agreement*). Increased runoff results in greater loads of salts, fecal coliforms, pathogens, and heavy metals (Pednekar et al., 2005; Paerl et al., 2006; Tibby and Tiller, 2007; Boxall et al., 2009) (*robust evidence*, *medium* to *high agreement*, depending on the pollutant). In some cases there are associated impacts on health. For instance, hospital admissions for gastrointestinal illness in elderly people increased by 10% when turbidity increased in the raw water of a drinking water plant even when treated using conventional procedures (Schwartz et al., 2000). However, positive impacts were also reported. For example, the risk of eutrophication was reduced when nutrients were flushed from lakes and estuaries by more frequent storms and hurricanes (Paerl and Huisman, 2008). For rivers, all reported impacts on water quality were negative. Greater runoff, instead of diluting pollution, swept more pollutants from the soil into watercourses (*robust evidence*, *medium* to *high agreement*) (Boxall et al., 2009; Loos et al., 2009; Benítez-Gilabert et al., 2010; Gascuel-Odoux et al., 2010; Howden et al., 2010; Saarinen et al., 2010; Tetzlaff et al., 2010; Macleod et al., 2012). Increased organic matter content impaired the quality of conventionally treated drinking water (Weatherhead and Howden, 2009). In streams in semiarid and arid areas, temperature changes had a stronger influence on the increase of organic matter, nitrates, and phosphorus than precipitation changes (Ozaki et al., 2003; Chang, 2004; Benítez-Gilabert et al., 2010) (*limited evidence*, *medium agreement*). Studies of impacts on groundwater quality are limited and mostly report elevated concentrations of fecal coliforms during the rainy season or after extreme rain events (*medium evidence*, *high agreement*), with varying response times (Curriero et al., 2001; Tumwine et al., 2002, 2003; Auld et al., 2004; Jean et al., 2006; Seidu et al., 2013). Given the widespread use of groundwater for municipal supply and minimal or lacking treatment of drinking water in poor regions, increased pollution is a source of concern (Jean et al., 2006; Seidu et al., 2013). Another concern is the nonlinearity (except for temperature) of relationships between water quality and climatic variables (*limited evidence*, *medium agreement*). In general, the linkages between observed effects on water quality and climate should be interpreted cautiously and at the local level, considering the type of water body, the pollutant of concern, the hydrological regime, and the many other possible sources of pollution (*high confidence*; Senhorst and Zwolsman, 2005; Whitehead et al., 2009a; Benítez-Gilabert et al., 2010; Howden et al., 2010; Kundzewicz and Krysanova, 2010; Ventela et al., 2011).

3.2.6. Soil Erosion and Sediment Load

Precipitation extremes in many regions have increased since 1950 (Seneviratne et al., 2012), which suggests an increase in rainfall erosivity that would enhance soil erosion and stream sediment loads. A warmer climate may affect soil moisture, litter cover, and biomass production and can bring about a shift in winter precipitation from snow to more erosive rainfall (Kundzewicz et al., 2007) or, in semiarid regions, an increase in wildfires with subsequent rainfall leading to intense erosive events (Nyman et al., 2011; Bussi et al., 2013). The effects of climate change on soil erosion and sediment load are frequently obscured by human agricultural and management activities (Walling, 2009).

Only few studies have isolated the contribution of climate change to observed trends in soil erosion and sediment load. In the Yellow River basin, where soil erosion results mostly from heavy rainfall, reduced precipitation (~10%) contributed about 30% to a total reduction in stream sediment loads reaching the sea during 2000–2005, compared to 1950–1968, with the remaining 70% attributable to sediment trapping in reservoirs and soil conservation measures (Wang et al., 2007; Miao et al., 2011). Dai et al. (2008), analyzing the decrease in sediment load of the Yangtze River over 1956–2002, found that climate change was responsible for an increase of about 3 ± 2%; most of the decline in its lower reaches was due to dam construction (Three Gorges Dam) and soil conservation measures.



	Location	Study period	Observation on water quality	Reference
1	Danube River, Bratislava, Slovakia	1926–2005	The water temperature is rising but the trend of the weighted long-term average temperature values resulted close to zero because of the interannual distribution of the mean monthly discharge.	Pekarova et al. (2008)
2	Purrumbete, Colac and Bullen Merri Lakes, Victoria, Australia	1984–2000	The increases in salinity and nutrient content were associated with the air temperature increase; salinity in addition was associated with variations in the effective precipitation.	Tibby and Tiller (2007)
3	Lake Tahoe, California and Nevada States, USA	1970–2007	Thermal stability resulting from a higher ambient temperature decreased the dissolved oxygen content.	Sahoo et al. (2010)
4	Neuse River Estuary, North Carolina, USA	1979–2003	Intense storms and hurricanes flushed nutrients from the estuary, reducing eutrophic conditions and the risk of algal blooms.	Paerl et al., (2006); Paerl and Huisman (2008)
5	River Meuse, western Europe	1976–2003	Increase of water temperature and the content of major elements and some heavy metals were associated with droughts. Algal blooms resulted from a higher nutrient content due to higher water temperature and longer residence time.	van Vliet and Zwolsman (2008)
6	Lake Taihu, Wuxi, Jiangsu, China	2007	The lake, already suffering from periodic cyanobacterial blooms, was affected by a very intensive bloom in May 2007 attributed to an unusually warm spring and leading to the presence of *Microcystis* toxins in the water. This forced two million people to drink bottled water for at least one week.	Qin et al. (2010)
7	Sau Reservoir, Spain	1964–2007	Stream flow variations were of greater significance than temperature increases in the depletion of dissolved oxygen.	Marcé et al. (2010)
8	22 upland waters in UK	1988–2002	Dissolved organic matter increased due to temperature increase but also due to rainfall variations, acid deposition, land use, and CO_2 enrichment.	Evans et al. (2005)
9	Coastal rivers from western Finland	1913–2007	Low pH values are associated with higher rainfall and river discharge in an acid sulfate soil basin.	Saarinen et al. (2010)
		1961–2007	Critical values of dissolved organic carbon is associated with higher rainfall and river discharge.	
10	15 pristine mountain rivers, northern Spain	1973–2005	For a semiarid area, there is a clear relationship between increases in air temperature and a higher nutrient and dissolved organic carbon content.	Benítez-Gilabert et al. (2010)
11	30 coastal rivers and groundwater of western France	1973–2007 (2–6 years)	Interannual variations in the nutrient content associated with air temperature, rainfall, and management practices changes. These effects were not observed in groundwater because of the delay in response time and the depuration of soil on water.	Gascuel-Odoux et al. (2010)
12	Girnock, Scotland	14 months	Higher risks of fecal pollution are clearly related to rainfall during the wet period.	Tetzlaff et al. (2010)
13	27 rivers in Japan	1987–1995	Increases in organic matter and sediment and decreases in the dissolved oxygen content are associated with increases in ambient temperature. Precipitation increases and variations are associated with an increase in the organic matter, sediments, and chemical oxygen demand content in water.	Ozaki et al. (2003)
14	Conestoga River Basin, Pennsylvania, USA	1977–1997	There is a close association between annual loads of total nitrogen and annual precipitation increases.	Chang (2004)
15	USA	1948–1994	Increased rainfall and runoff are associated with site-specific outbreaks of waterborne disease.	Curriero et al. (2001)
16	Northern and eastern Uganda	1999–2001, 2004, 2007	Elevated concentrations of fecal coliforms are observed in groundwater-fed water supplies during the rainy season.	Tumwine et al. (2002, 2003); Taylor et al. (2009)
17	Taiwan, China	1998	The probability of detecting cases of enterovirus infection was greater than 50%, with rainfall rates >31 mm h^{-1}. The higher the rainfall rate, the higher the probability of an enterovirus epidemic.	Jean et al. (2006)
18	Rhine Basin	1980–2001	Nutrient content in rivers followed seasonal variations in precipitation which were also linked to erosion within the basin.	Loos et al. (2009)
19	River Thames, England	1868–2008	Higher nutrient contents were associated to changes in river runoff and land use.	Howden et al. (2010)

Figure 3-2 | Observations of the impacts of climate on water quality.

Potential impacts of climate change on soil erosion and sediment production are of concern in regions with pronounced glacier retreat (Walling, 2009). Glacial rivers are expected to discharge more meltwater, which may increase sediment loads. However, the *limited evidence* is inconclusive for a global diagnosis of sediment load changes; there are both decreasing (e.g., Iceland; Lawler et al., 2003) and increasing trends (Patagonia; Fernandez et al., 2011). So far, there is no clear evidence that the frequency or magnitude of shallow landslides has changed over past decades (Huggel et al., 2012), even in regions with relatively complete event records (e.g., Switzerland; Hilker et al., 2009). Increased landslide impacts (measured by casualties or losses) in south and Southeast Asia, where landslides are triggered predominantly by monsoon and tropical cyclone activity, are largely attributed to population growth leading to increased exposure (Petley, 2012).

In summary, there is *limited evidence* and *low agreement* that anthropogenic climate change has made a significant contribution to soil erosion, sediment loads, and landslides. The available records are limited in space and time, and evidence suggests that, in most cases, the impacts of land use and land cover changes are more significant than those of climate change.

3.2.7. Extreme Hydrological Events and their Impacts

There is *low confidence*, due to *limited evidence*, that anthropogenic climate change has affected the frequency and magnitude of floods at global scale (Kundzewicz et al., 2013). The strength of the evidence is limited mainly by lack of long-term records from unmanaged catchments. Moreover, in the attribution of detected changes it is difficult to distinguish the roles of climate and human activities (Section 3.2.1). However, recent detection of trends in extreme precipitation and discharge in some catchments implies greater risks of flooding at regional scale (*medium confidence*). More locations show increases in heavy precipitation than decreases (Seneviratne et al., 2012). Flood damage costs worldwide have been increasing since the 1970s, although this is partly due to increasing exposure of people and assets (Handmer et al., 2012).

There is no strong evidence for trends in observed flooding in the USA (Hirsch and Ryberg, 2012), Europe (Mudelsee et al., 2003; Stahl et al., 2010; Benito and Machado, 2012; Hannaford and Hall, 2012), South America, and Africa (Conway et al., 2009). However, at smaller spatial scales, an increase in annual maximum discharge has been detected in parts of northwestern Europe (Petrow and Merz, 2009; Giuntoli et al., 2012; Hattermann et al., 2012), while a decrease was observed in southern France (Giuntoli et al., 2012). Flood discharges in the lower Yangtze basin increased over the last 40 years (Jiang et al., 2008; Zhang et al., 2009), and both upward and downward trends were identified in four basins in the northwestern Himalaya (Bhutiyani et al., 2008). In Australia, only 30% of 491 gauge stations showed trends at the 10% significance level, with decreasing magnitudes in southern regions and increasing magnitudes in the northern regions (Ishak et al., 2010). In Arctic rivers dominated by a snowmelt regime, there is no general trend in flood magnitude and frequency (Shiklomanov et al., 2007). In Nordic countries, significant changes since the mid-20th century are mostly toward earlier seasonal flood peaks, but flood magnitudes show contrasting trends, driven by temperature and precipitation, in basins with and without glaciers increasing peaks in the former and decreasing peaks in the latter (Wilson et al., 2010; Dahlke et al., 2012). Significant trends at almost one-fifth of 160 stations in Canada were reported, most of them decreases in snowmelt-flood magnitudes (Cunderlik and Ouarda, 2009). Similar decreases were found for spring and annual maximum flows (Burn et al., 2010).

Attribution has been addressed by Hattermann et al. (2012), who identified parallel trends in precipitation extremes and flooding in Germany, which for the increasing winter floods are explainable in terms of increasing frequency and persistence of circulation patterns favorable to flooding (Petrow et al., 2009). It is *very likely* that the observed intensification of heavy precipitation is largely anthropogenic (Min et al., 2011; see also Section 3.2.1).

Socioeconomic losses from flooding are increasing (*high confidence*), although attribution to anthropogenic climate change is established only seldom (Pall et al., 2011). Reported flood damages (adjusted for inflation) have increased from an average of US$7 billion per year in the 1980s to about US$24 billion per year in 2011 (Kundzewicz et al., 2013). Economic, including insured, flood disaster losses are higher in developed countries, while fatality rates and economic losses expressed as a proportion of gross domestic product are higher in developing countries. Since 1970, the annual number of flood-related deaths has been in the thousands, with more than 95% in developing countries (Handmer et al., 2012). There is *high confidence* (*medium evidence*, *high agreement*) that greater exposure of people and assets, and societal factors related to population and economic growth, contributed to the increased losses (Handmer et al., 2012; Kundzewicz et al., 2013). When damage records are normalized for changes in exposure and vulnerability (Bouwer, 2011), most studies find no contribution of flooding trends to the trend in losses (Barredo, 2009; Hilker et al., 2009; Benito and Machado, 2012), although there are exceptions (Jiang et al., 2005; Chang et al., 2009).

Assessments of observed changes in "drought" depend on the definition of drought (meteorological, agricultural, or hydrological) and the chosen drought index (e.g., consecutive dry days, Standardized Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Standardized Runoff Index (SRI); see Seneviratne et al., 2012). Meteorological (rainfall) and agricultural (soil moisture) droughts have become more frequent since 1950 (Seneviratne et al., 2012) in some regions, including southern Europe and western Africa, but in others (including the southern USA; Chen et al., 2012) there is no evidence of change in frequency (WGI AR5 Chapter 2).

Very few studies have considered variations over time in hydrological (streamflow) drought, largely because there are few long records from catchments without direct human interventions. A trend was found toward lower summer minimum flows for 1962–2004 in small catchments in southern and Eastern Europe, but there was no clear trend in northern or Western Europe (Stahl et al., 2010). Models can reproduce observed patterns of drought occurrence (e.g., Prudhomme et al., 2011), but as with climate models their outputs can be very divergent. In simulations of drought at the global scale in 1963–2000 with an ensemble of hydrological models, strong correlations were noted between El Niño-

Southern Oscillation (ENSO) events and hydrological droughts, and—particularly in dry regions—low correlations between meteorological and hydrological droughts, which suggests that hydrological droughts cannot necessarily be inferred from rainfall deficits (van Huijgevoort et al., 2013).

3.3. Drivers of Change for Freshwater Resources

3.3.1. Climatic Drivers

Precipitation and potential evaporation are the main climatic drivers controlling freshwater resources. Precipitation is strongly related to atmospheric water vapor content, because saturation specific humidity depends on temperature: warmer air can hold much more water vapor. Temperature has increased in recent decades while surface and tropospheric relative humidity have changed little (WGI AR5 Chapter 2). Among other climatic drivers are atmospheric CO_2, which affects plant transpiration (Box CC-VW), and deposited black carbon and dust, both of which, even in very small concentrations, enhance melting of snow and ice by reducing the surface albedo.

Uncertainty in the climatic drivers is due mainly to internal variability of the atmospheric system, inaccurate modeling of the atmospheric response to external forcing, and the external forcing itself as described by the Representative Concentration Pathways (RCPs; Section 1.1.3). Internal variability and variation between models account for all of the uncertainty in precipitation in the first few decades of the 21st century in Coupled Model Intercomparison Project Phase 3 (CMIP3) projections (Hawkins and Sutton, 2011). The contribution of internal variability diminishes progressively. By no later than mid-century, most of the uncertainty in precipitation is due to discrepancies between models, and divergent scenarios never contribute more than one-third of the uncertainty. In contrast, the uncertainty in temperature (WGI AR5 Chapter 11) is due mostly to divergent scenarios.

CMIP5 simulations of the water cycle during the 21st century (WGI AR5 Chapter 12), with further constraints added here from 20th century observations, can be summarized as follows:

- Surface temperature, which affects the vapor-carrying capacity of the atmosphere and the ratio of snowfall to precipitation, increases non-uniformly (*very high confidence*), probably by about 1.5 times more over land than over ocean.
- Warming is greatest over the Arctic (*very high confidence*), implying latitudinally variable changes in snowmelt and glacier mass budgets.
- Less precipitation falls as snow and snow cover decreases in extent and duration (*high confidence*). In the coldest regions, however, increased winter snowfall outweighs increased summer snowmelt.
- Wet regions and seasons become wetter and dry regions and seasons become drier (*high confidence*), although one observational analysis (Sun et al., 2012) is discordant; moreover the models tend to underestimate observed trends in precipitation (Noake et al., 2012) and its observed sensitivity to temperature (Liu et al., 2012).
- Global mean precipitation increases in a warmer world (*virtually certain*), but with substantial variations, including some decreases, from region to region. Precipitation tends to decrease in subtropical latitudes, particularly in the Mediterranean, Mexico and Central America, and parts of Australia, and to increase elsewhere, notably at high northern latitudes and in India and parts of central Asia (*likely* to *very likely*; WGI AR5 Figure 12-41). However, precipitation changes generally become statistically significant only when temperature rises by at least 1.4°C, and in many regions projected 21st century changes lie within the range of late 20th century natural variability (Mahlstein et al., 2012).
- Changes in evaporation have patterns similar to those of changes in precipitation, with moderate increases almost everywhere, especially at higher northern latitudes (WGI AR5 Figure 12-25). Scenario-dependent decreases of soil moisture are widespread, particularly in central and southern Europe, southwestern North America, Amazonia, and southern Africa (*medium* to *high confidence*; WGI AR5 Figure 12-23; WGI AR5 Section 12.4.5.3).

More intense extreme precipitation events are expected (IPCC, 2012). One proposed reason is the projected increase in specific humidity: intense convective precipitation in short periods (less than 1 hour) tends to "empty" the water vapor from the atmospheric column (Utsumi et al., 2011; Berg et al., 2013). Annual maxima of daily precipitation that are observed to have 20-year return periods in 1986–2005 are projected to have shorter return periods in 2081–2100: about 14 years for RCP2.6, 11 years for RCP4.5, and 6 years for RCP8.5 (Kharin et al., 2013). Unlike annual mean precipitation, for which the simulated sensitivity to warming is typically 1.5 to 2.5% K^{-1}, the 20-year return amount of daily precipitation typically increases at 4 to 10% K^{-1}. Agreement between model-simulated extremes and reanalysis extremes is good in the extratropics but poor in the tropics, where there is *robust evidence* of greater sensitivity (10 ± 4% K^{-1}, O'Gorman, 2012). In spite of the intrinsic uncertainty of sampling infrequent events, variation between models is the dominant contributor to uncertainty. Model-simulated changes in the incidence of meteorological (rainfall) droughts vary widely, so that there is at best *medium confidence* in projections (Seneviratne et al., 2012). Regions where droughts are projected to become longer and more frequent include the Mediterranean, central Europe, central North America, and southern Africa.

3.3.2. Non-Climatic Drivers

In addition to impacts of climate change, the future of freshwater systems will be impacted strongly by demographic, socioeconomic, and technological changes, including lifestyle changes. These change both exposure to hazard and requirements for water resources. A wide range of socioeconomic futures can produce similar climate changes (van Vuuren et al., 2012), meaning that certain projected hydrological changes (Section 3.4) can occur under a wide range of future demographic, social, economic, and ecological conditions. Similarly, the same future socioeconomic conditions can be associated with a range of different climate futures.

Changing land use is expected to affect freshwater systems strongly in the future. For example, increasing urbanization may increase flood hazards and decrease groundwater recharge. Of particular importance for freshwater systems is future agricultural land use, especially irrigation, which accounts for about 90% of global water consumption and severely impacts freshwater availability for humans and ecosystems (Döll, 2009).

Owing mainly to population and economic growth but also to climate change, irrigation may significantly increase in the future. The share of irrigation from groundwater is expected to increase owing to increased variability of surface water supply caused by climate change (Taylor R. et al., 2013a).

3.4. Projected Hydrological Changes

3.4.1. Methodological Developments in Hydrological Impact Assessment

Most recent studies of the potential impact of climate change on hydrological characteristics have used a small number of climate scenarios. An increasing number has used larger ensembles of regional or global models (e.g., Chiew et al., 2009; Gosling et al., 2010; Arnell, 2011; Bae et al., 2011; Jackson et al., 2011; Olsson et al., 2011; Kling et al., 2012; Arnell and Gosling, 2013). Some studies have developed "probability distributions" of future impacts by combining results from multiple climate projections and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke et al., 2009b; Manning et al., 2009; Christierson et al., 2012; Liu et al., 2013). These studies conclude that the relative weightings given are typically less important in determining the distribution of future impacts than the initial selection of climate models considered. Very few impact studies (Dankers et al., 2013; Hanasaki et al., 2013; Portmann et al., 2013; Schewe et al., 2013) have so far used scenarios based on CMIP5 climate models, and these have used only a small subset.

Most assessments have used a hydrological model with the "delta method" to create scenarios, which applies projected changes in climate derived from a climate model either to an observed baseline or with a stochastic weather generator. Several approaches to the construction of scenarios at the catchment scale have been developed (Fowler et al., 2007), including dynamical downscaling using regional climate models and a variety of statistical approaches (e.g., Fu et al., 2013). Systematic evaluations of different methods have demonstrated that estimated impacts can be very dependent on the approach used to downscale climate model data, and the range in projected change between downscaling approaches can be as large as the range between different climate models (Quintana Segui et al., 2010; Chen J. et al., 2011). An increasing number of studies (e.g., Fowler and Kilsby, 2007; Hagemann et al., 2011; Kling et al., 2012; Teutschbein and Seibert, 2012; Veijalainen et al., 2012; Weiland et al., 2012a) have run hydrological models with bias-corrected input from regional or global climate model output (van Pelt et al., 2009; Piani et al., 2010; Yang et al., 2010), rather than by applying changes to an observed baseline. The range between different bias correction methods can be as large as the range between climate models (Hagemann et al., 2011), although this is not always the case (Chen C. et al., 2011; Muerth et al., 2013). Some studies (e.g., Falloon and Betts, 2006, 2010; Hirabayashi et al., 2008; Nakaegawa et al., 2013) have examined changes in global-scale river runoff as simulated directly by a high-resolution climate model, rather than by an "off-line" hydrological model. Assessments of the ability of climate models directly to simulate current river flow regimes (Falloon et al., 2011; Weiland et al., 2012b) show that performance depends largely on simulated precipitation and is better for large basins, but the *limited evidence* suggests that direct estimates of change are smaller than off-line estimates (Hagemann et al., 2013).

The effects of hydrological model parameter uncertainty on simulated runoff changes are typically small when compared with the range from a large number of climate scenarios (Steele-Dunne et al., 2008; Cloke et al., 2010; Vaze et al., 2010; Arnell, 2011; Lawrence and Haddeland, 2011). However, the effects of hydrological model structural uncertainty on projected changes can be substantial (Dankers et al., 2013; Hagemann et al., 2013; Schewe et al., 2013), owing to differences in the representation of evaporation and snowmelt processes. In some regions (e.g., high latitudes; Hagemann et al., 2013) with reductions in precipitation (Schewe et al., 2013), hydrological model uncertainty can be greater than climate model uncertainty—although this is based on small numbers of climate models. Much of the difference in projected changes in evaporation is due to the use of different empirical formulations (Milly and Dunne, 2011). In a study in southeast Australia, the effects of hydrological model uncertainty were small compared with climate model uncertainty, but all the hydrological models used the same potential evaporation data (Teng et al., 2012).

Among other approaches to impact assessment, an inverse technique (Cunderlik and Simonovic, 2007) starts by identifying the hydrological changes that would be critical for a system and then uses a hydrological model to determine the meteorological conditions that trigger those changes; the future likelihood of these conditions is estimated by inspecting climate model output, as in a catchment study in Turkey (Fujihara et al., 2008a,b). Another approach constructs response surfaces relating sensitivity of a hydrological indicator to changes in climate. Several studies have used a water-energy balance framework (based on Budyko's hypothesis and formula) to characterize the sensitivity of average annual runoff to changes in precipitation and evaporation (Donohue et al., 2011; Renner and Bernhofer, 2012; Renner et al., 2012). A response surface showing change in flood magnitudes was constructed by running a hydrological model with systematically varying changes in climate (Prudhomme et al., 2010). This approach shows the sensitivity of a system to change, and also allows rapid assessment of impacts under specific climate scenarios which can be plotted on the response surface.

3.4.2. Evapotranspiration, Soil Moisture, and Permafrost

Based on global and regional climate models as well as physical principles, potential evapotranspiration over most land areas is *very likely* to increase in a warmer climate, thereby accelerating the hydrologic cycle (WGI AR5 Chapter 12). Long-term projections of actual evapotranspiration are uncertain in both magnitude and sign. They are affected not only by rising temperatures but also by changing net radiation and soil moisture, decreases in bulk canopy conductance associated with rising CO_2 concentrations, and vegetation changes related to climate change (Box CC-VW; Katul and Novick, 2009). Projections of the response of potential evapotranspiration to a warming climate are also uncertain. Based on six different methodologies, an increase in potential evapotranspiration was associated with global warming (Kingston et al., 2009). Regionally, increases are projected in southern Europe, Central America, southern Africa, and Siberia (Seneviratne et al., 2010). The accompanying decrease in soil moisture increases the

Box 3-1 | Case Study: Himalayan Glaciers

The total freshwater resource in the Himalayan glaciers of Bhutan, China, India, Nepal, and Pakistan is known only roughly; estimates range from 2100 to 5800 Gt (Bolch et al., 2012). Their mass budgets have been negative on average for the past 5 decades. The loss rate may have become greater after about 1995, but it has not been greater in the Himalaya than elsewhere. A recent large-scale measurement, highlighted in Figure 3-3, is the first well-resolved, region-wide measurement of any component of the Himalayan water balance. It suggests strongly that the conventional measurements, mostly on small, accessible glaciers, are not regionally representative.

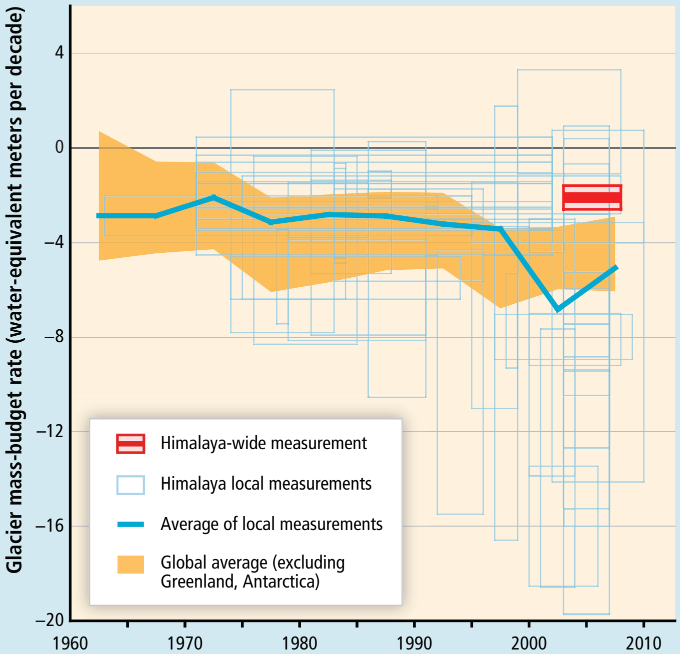


Figure 3-3 | All published glacier mass balance measurements from the Himalaya (based on Bolch et al., 2012). To emphasize the variability of the raw information, each measurement is shown as a box of height ±1 standard deviation centred on the average balance (±1 standard error for multiannual measurements). Region-wide measurement (Kääb et al., 2012) was by satellite laser altimetry. Global average (WGI AR5 Chapter 4) is shown as a 1-sigma confidence region.

Glacier mass changes for 2006–2100 were projected by simulating the response of a glacier model to CMIP5 projections from 14 General Circulation Models (GCMs) (Radić et al., 2013). Results for the Himalaya range between 2% gain and 29% loss to 2035; to 2100, the range of losses is 15 to 78% under RCP4.5. The model-mean loss to 2100 is 45% under RCP4.5 and 68% under RCP8.5 (*medium confidence*). It is *virtually certain* that these projections are more reliable than an earlier erroneous assessment (Cruz et al., 2007) of complete disappearance by 2035.

At the catchment scale, projections do not yet present a detailed region-wide picture. However the GCM-forced simulations of Immerzeel et al. (2013) in Kashmir and eastern Nepal show runoff increasing throughout the century. Peak ice meltwater is reached in mid- to late-century, but increased precipitation overcompensates for the loss of ice.

The growing atmospheric burden of anthropogenic black carbon implies reduced glacier albedo, and measurements in eastern Nepal by Yasunari et al. (2010) suggest that this could yield 70 to 200 mm yr^{-1} of additional meltwater. Deposited soot may outweigh the greenhouse effect as a radiative forcing agent for snowmelt (Qian et al., 2011).

The hazard due to moraine-dammed ice-marginal lakes continues to increase. In the western Himalaya, they are small and stable in size, while in Nepal and Bhutan they are more numerous and larger, and most are growing (Gardelle et al., 2011). There has been little progress on the predictability of dam failure but, of five dams that have failed since 1980, all had frontal slopes steeper than 10° before failure and much gentler slopes afterward (Fujita et al., 2013). This is a promising tool for evaluating the hazard in detail.

The relative importance of Himalayan glacier meltwater decreases downstream, being greatest where the runoff enters dry regions in the west and becoming negligible in the monsoon-dominated east (Kaser et al., 2010). In the mountains, however, dependence on and vulnerability to glacier meltwater are of serious concern when measured per head of population.

risk of extreme hot days (Seneviratne et al., 2006; Hirschi et al., 2011) and heat waves. For a range of scenarios, soil moisture droughts lasting 4 to 6 months double in extent and frequency, and droughts longer than 12 months become three times more common, between the mid-20th century and the end of the 21st century (Sheffield and Wood, 2008). Because of strong natural variability, the generally monotonic projected increases are statistically indistinguishable from the current climate.

Changes consistent with warming are also evident in the freshwater systems and permafrost of northern regions. The area of permafrost is projected to continue to decline over the first half of the 21st century in all emissions scenarios (WGI AR5 Figure 4-18). Under RCP2.6, the permafrost area is projected to stabilize at near 37% less than the 20th century area.

3.4.3. Glaciers

All projections for the 21st century (WGI AR5 Chapter 13) show continued mass loss from glaciers. In glacierized catchments, runoff reaches an annual maximum in summer. As the glaciers shrink, their relative contribution decreases and the annual runoff peak shifts toward spring (e.g., Huss, 2011). This shift is expected with *very high confidence* in most regions, although not, for example, in the eastern Himalaya, where the monsoon and the melt season coincide. The relative importance of high-summer glacier meltwater can be substantial, for example contributing 25% of August discharge in basins draining the European Alps, with area about 105 km^2 and only 1% glacier cover (Huss, 2011). Glacier meltwater also increases in importance during droughts and heat waves (Koboltschnig et al., 2007).

If the warming rate is constant, and if, as expected, ice melting per unit area increases and total ice-covered area decreases, the total annual yield passes through a broad maximum: "peak meltwater." Peak-meltwater dates have been projected between 2010 and 2050 (parts of China, Xie et al., 2006); 2010–2040 (European Alps, Huss, 2011); and mid- to late-century (glaciers in Norway and Iceland, Jóhannesson et al., 2012). Note that the peak can be dated only relative to a specified reference date. Declining yields relative to various dates in the past have been detected in some observational studies (Table 3-1); that is, a peak has been passed already. There is *medium confidence* that the peak response to 20th- and 21st-century warming will fall within the 21st century in many inhabited glacierized basins, where at present society is benefitting from a transitory "meltwater dividend." Variable forcing leads to complex variations of both the melting rate and the extent of ice, which depend on each other.

If they are in equilibrium, glaciers reduce the interannual variability of water resources by storing water during cold or wet years and releasing it during warm years (Viviroli et al., 2011). As glaciers shrink, however, their diminishing influence may make the water supply less dependable.

3.4.4. Runoff and Streamflow

Many of the spatial gaps identified in AR4 have been filled to a very large extent by catchment-scale studies of the potential impacts of climate change on streamflow. The projected impacts in a catchment depend on the sensitivity of the catchment to change in climatic characteristics and on the projected change in the magnitude and seasonal distribution of precipitation, temperature, and evaporation. Catchment sensitivity is largely a function of the ratio of runoff to precipitation: the smaller the ratio, the greater the sensitivity. Proportional changes in average annual runoff are typically between one and three times as large as proportional changes in average annual precipitation (Tang and Lettenmaier, 2012).

Projected scenario-dependent changes in runoff at the global scale, mostly from CMIP3 simulations, exhibit a number of consistent patterns (e.g., Hirabayashi et al., 2008; Döll and Zhang, 2010; Fung et al., 2011; Murray et al., 2012; Okazaki et al., 2012; Tang and Lettenmaier, 2012; Weiland et al., 2012a; Arnell and Gosling, 2013; Nakaegawa et al., 2013; Schewe et al., 2013). Average annual runoff is projected to increase at high latitudes and in the wet tropics, and to decrease in most dry tropical regions. However, for some regions there is very considerable uncertainty in the magnitude and direction of change, specifically in China, south Asia, and large parts of South America. Both the patterns of change and the uncertainty are driven largely by projected changes in precipitation, particularly across south Asia. Figure 3-4 shows the average percentage change in average annual runoff for an increase in global average temperature of 2°C above the 1980–2010 mean, averaged across five CMIP5 climate models and 11 hydrological models. The pattern of change in Figure 3-4 is different in some regions from the pattern shown in WGI AR5 Figure 12-24, largely because it is based on fewer climate models.

The seasonal distribution of change in streamflow varies primarily with the seasonal distribution of change in precipitation, which in turn varies between scenarios. Figure 3-5 illustrates this variability, showing the percentage change in monthly average runoff in a set of catchments from different regions using scenarios from seven climate models, all scaled to represent a 2°C increase in global mean temperature above the 1961–1990 mean. One of the climate models is separately highlighted, and for that model the figure also shows changes with a 4°C rise in temperature. In the Mitano catchment in Uganda, for example, there is a nonlinear relationship between amount of climate change and hydrological response. Incorporating uncertainty in hydrological model structure (Section 3.4.1) would increase further the range in projected impacts at the catchment scale.

There is a much more consistent pattern of future seasonal change in areas currently influenced by snowfall and snowmelt. A global analysis (Adam et al., 2009) with multiple climate scenarios shows a consistent shift to earlier peak flows, except in some regions where increases in precipitation are sufficient to result in increased, rather than decreased, snow accumulation during winter. The greatest changes are found near the boundaries of regions that currently experience considerable snowfall, where the marginal effect of higher temperatures on snowfall and snowmelt is greatest.

3.4.5. Groundwater

While the relation between groundwater and climate change was rarely investigated before 2007, the number of studies and review papers

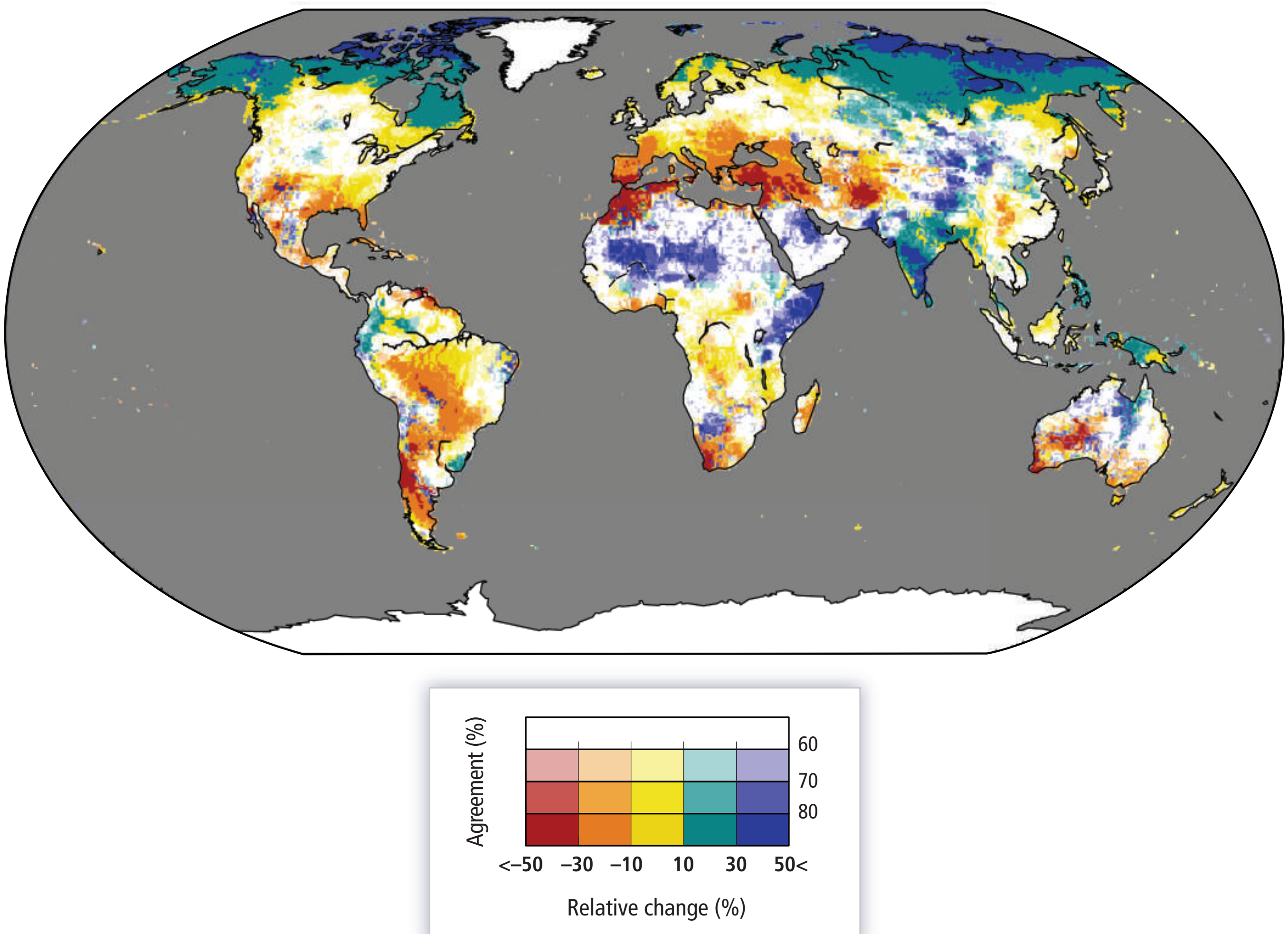


Figure 3-4 | Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980–2010 (2.7°C above pre-industrial). Color hues show the multi-model mean change across 5 General Circulation Models (GCMs) and 11 Global Hydrological Models (GHMs), and saturation shows the agreement on the sign of change across all 55 GHM–GCM combinations (percentage of model runs agreeing on the sign of change) (Schewe et al., 2013).

(Green et al., 2011; Taylor R. et al., 2013a) has increased significantly since then. Ensemble studies, relying on between 4 and 20 climate models, of the impact of climate change on groundwater recharge and partially also on groundwater levels were done for the globe (Portmann et al., 2013), all of Australia (Crosbie et al., 2013a), the German Danube basin (Barthel et al., 2010), aquifers in Belgium and England (Goderniaux et al., 2011; Jackson et al., 2011), the Pacific coast of the USA and Canada (Allen et al., 2010), and the semiarid High Plains aquifer of the USA (Ng et al., 2010; Crosbie et al., 2013b). With three exceptions, simulations were run under only one GHG emissions scenario. The range over the climate models of projected groundwater changes was large, from significant decreases to significant increases for the individual study areas, and the range of percentage changes of projected groundwater recharge mostly exceeded the range of projected precipitation changes. The uncertainties in projected groundwater recharge that originate in the hydrological models have not yet been explored. There are only a few studies of the impacts on groundwater of vegetation changes in response to climate change and CO_2 increase (Box CC-VW). Nor are there any studies on the impact of climate-driven changes of land use on groundwater recharge, even though projected increases in precipitation and streamflow variability due to climate change are expected to lead to increased groundwater abstraction (Taylor R. et al., 2013a), lowering groundwater levels and storage.

Under any particular climate scenario, the areas where total runoff (sum of surface runoff and groundwater recharge) is projected to increase (or decrease) roughly coincide with the areas where groundwater recharge and thus renewable groundwater resources are projected to increase (or decrease) (Kundzewicz and Döll, 2009). Changes in precipitation intensity affect the fraction of total runoff that recharges groundwater. Increased precipitation intensity may decrease groundwater recharge owing to exceedance of the infiltration capacity (typically in humid areas), or may increase it owing to faster percolation through the root zone and thus reduced evapotranspiration (typically in semiarid areas) (Liu, 2011; Taylor R. et al., 2013b). The sensitivity of groundwater recharge and levels to climate change is diminished by perennial vegetation, fine-grained soils, and aquitards and is enhanced by annual cropping, sandy soils, and unconfined (water table) aquifers (van Roosmalen et al., 2007; Crosbie et al., 2013b). The sensitivity of groundwater recharge change to precipitation change was found to be highest for low groundwater

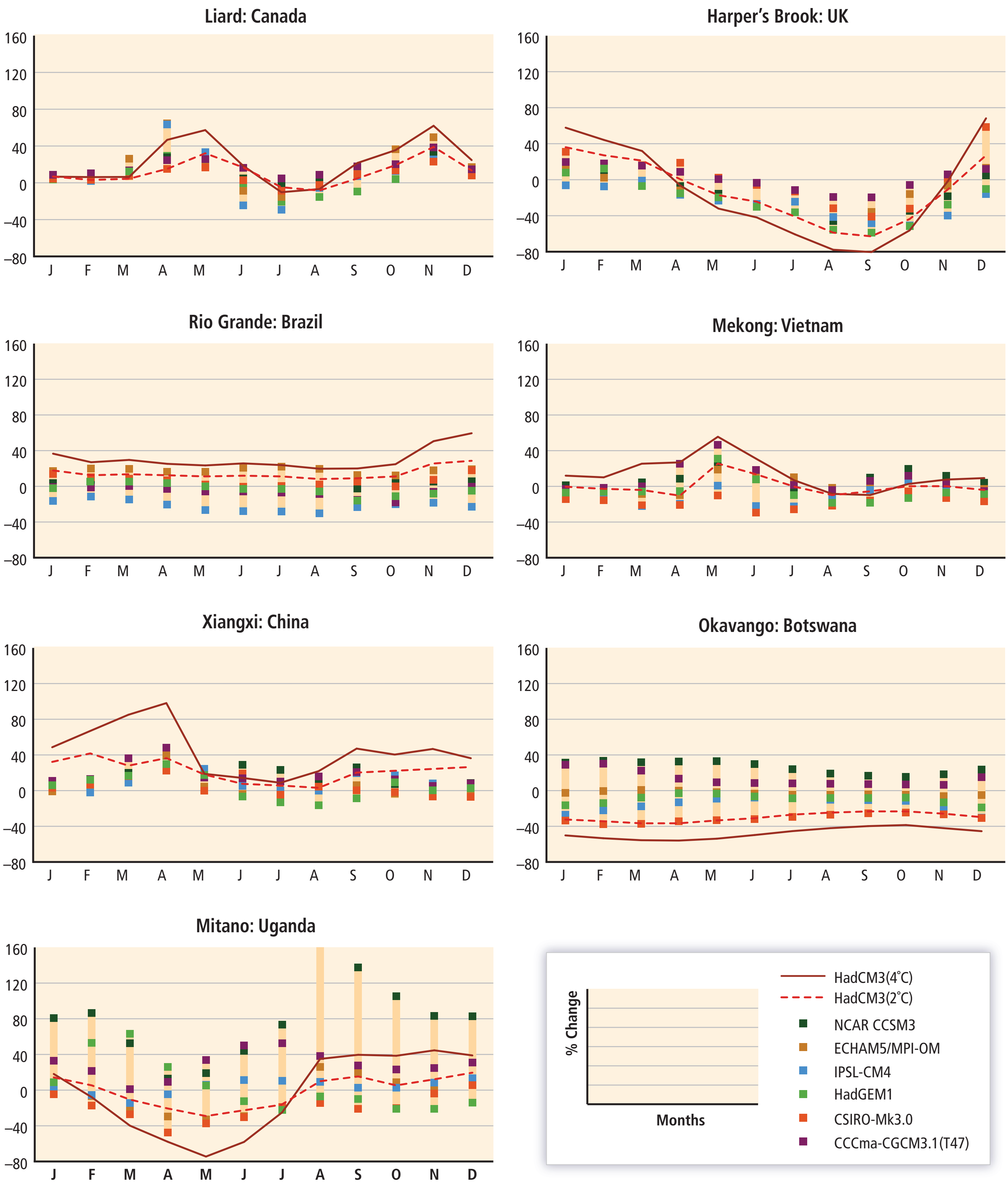


Figure 3-5 | Change in mean monthly runoff across seven climate models in seven catchments, with a 2°C increase in global mean temperature above 1961–1990 (Kingston and Taylor, 2010; Arnell, 2011; Hughes et al., 2011; Kingston et al., 2011; Nobrega et al., 2011; Thorne, 2011; Xu et al., 2011). One of the seven climate models (HadCM3) is highlighted separately, showing changes with both a 2°C increase (dotted line) and a 4°C increase (solid line).

recharge and lowest for high groundwater recharge, the ratio of recharge change to precipitation change ranging from 1.5 to 6.0 in the semiarid High Plains aquifer (Crosbie et al., 2013b). Decreasing snowfall may lead to lower groundwater recharge even if precipitation remains constant; at sites in the southwestern USA, snowmelt provides at least 40 to 70% of groundwater recharge, although only 25 to 50% of average annual precipitation falls as snow (Earman et al., 2006).

Climate change affects coastal groundwater not only through changes in groundwater recharge but also through sea level rise which, together with the rate of groundwater pumping, determines the location of the saltwater/freshwater interface. Although most confined aquifers are expected to be unaffected by sea level rise, unconfined aquifers are expected to suffer from saltwater intrusion (Werner et al., 2012). The volume available for freshwater storage is reduced if the water table cannot rise freely as the sea level rises (Masterson and Garabedian, 2007; Werner et al., 2012). This happens where land surfaces are low lying, for example, on many coral islands and in deltas, but also where groundwater discharges to streams. If the difference between the groundwater table and sea level is decreased by 1 m, the thickness of the unconfined freshwater layer decreases by roughly 40 m (Ghyben-Herzberg relation). Deltas are also affected by storm surges that drive saltwater into stream channels, contaminating the underlying fresh groundwater from above (Masterson and Garabedian, 2007). In three modeling studies, the impact of sea level rise on groundwater levels was found to be restricted to areas within 10 km from the coast (Carneiro et al., 2010; Oude Essink et al., 2010; Yechieli et al., 2010). Saltwater intrusion due to sea level rise is mostly a very slow process that may take several centuries to reach equilibrium (Webb and Howard, 2011). Even small rates of groundwater pumping from coastal aquifers are expected to lead to stronger salinization of the groundwater than sea level rise during the 21st century (Ferguson and Gleeson, 2012; Loaiciga et al., 2012).

Changes in groundwater recharge also affect streamflow. In the Mitano basin in Uganda, mean global temperature increases of 4°C or more with respect to 1961–1990 are projected to decrease groundwater outflow to the river so much that the spring discharge peak disappears and the river flow regime changes from bimodal to unimodal (one seasonal peak only) (Kingston and Taylor, 2010; Figure 3-5). Changing groundwater tables affect land surface energy fluxes, including evaporation, and thus feed back on the climate system, in particular in semiarid areas where the groundwater table is within 2 to 10 m of the surface (Jiang et al., 2009; Ferguson and Maxwell, 2010).

3.4.6. Water Quality

Climate change affects the quality of water through a complex set of natural and anthropogenic mechanisms working concurrently in parallel and in series. Projections under climate change scenarios are difficult, both to perform and interpret, because they require not only integration of the climate models with those used to analyze the transportation and transformation of pollutants in water, soil, and air but also the establishment of a proper baseline (Arheimer et al., 2005; Andersen et al., 2006; Wilby et al., 2006; Ducharne, 2008; Marshall and Randhir, 2008; Bonte and Zwolsman, 2010; Towler et al., 2010; Trolle et al., 2011; Rehana and Mujumdar, 2012). The models have different spatial scales and have to be adapted and calibrated to local conditions for which adequate and appropriate information is needed. In consequence, there are few projections of the impacts of climate change on water quality; where available, their uncertainty is high. It is evident, however, that water quality projections depend strongly on (1) local conditions; (2) climatic and environmental assumptions; and (3) the current or reference pollution state (Chang, 2004; Whitehead et al., 2009a,b; Bonte and Zwolsman, 2010; Kundzewicz and Krysanova, 2010; Sahoo et al., 2010; Trolle et al., 2011). Most projections suggest that future negative impacts will be similar in kind to those already observed in response to change and variability in air and water temperature, precipitation, and storm runoff, and to many confounding anthropogenic factors (Chang, 2004; Whitehead et al., 2009a). This holds for natural and artificial reservoirs (Brikowski, 2008; Ducharne, 2008; Marshall and Randhir, 2008; Loos et al., 2009; Bonte and Zwolsman, 2010; Qin et al., 2010; Sahoo et al., 2010; Trolle et al., 2011), rivers (Andersen et al., 2006; Whitehead et al., 2009a,b; Bowes et al., 2012) and groundwater (Butscher and Huggenberger, 2009; Rozemeijer et al., 2009).

3.4.7. Soil Erosion and Sediment Load

Heavy rainfalls are *likely* to become more intense and frequent during the 21st century in many parts of the world (Seneviratne et al., 2012; WGI AR5 Chapter 11), which may lead to more intense soil erosion even if the total rainfall does not increase. At the global scale, soil erosion simulated assuming doubled CO_2 is projected to increase about 14% by the 2090s, compared to the 1980s (9% attributed to climate change and 5% to land use change), with increases by as much as 40 to 50% in Australia and Africa (Yang et al., 2003). The largest increases are expected in semiarid areas, where extreme events may contribute about half of total erosion; for instance, in Mediterranean Spain 43% of sediment yield over the time period 1990–2009 was produced by a single event (Bussi et al., 2013). In agricultural lands in temperate regions, soil erosion may respond to more intense erosion in complex nonlinear ways; for instance in the UK a 10% increase in winter rainfall (i.e., during early growing season) could increase annual erosion of arable land by up to 150% (Favis-Mortlock and Boardman, 1995), while in Austria a simulation for 2070–2099 projected a decrease of rainfall by 10 to 14% in erosion-sensitive months and thus a decline in soil erosion by 11 to 24% (Scholz et al., 2008). Land management practices are critical for mitigating soil erosion under projected climate change. In China's Loess Plateau, four GCMs coupled to an erosion model show soil erosion increasing by –5 to 195% of soil loss during 2010–2039 under conventional tillage, for three emission scenarios (*Special Report on Emission Scenarios* (SRES) A2 and B2, and IS92a), whereas under conservation tillage they show decreases of 26 to 77% (Li et al., 2011).

Climate change will also affect the sediment load in rivers by altering water discharge and land cover. For example, an increase in water discharge of 11 to 14% in two Danish rivers under the SRES A2 emission scenario was projected to increase the annual suspended sediment load by 9 to 36% during 2071–2100 (Thodsen et al., 2008). Increases in total precipitation, increased runoff from glaciers, permafrost degradation, and the shift of precipitation from snow to rain will further increase soil erosion and sediment loads in colder regions (Lu et al., 2010). In a major

Frequently Asked Questions

FAQ 3.1 | How will climate change affect the frequency and severity of floods and droughts?

Climate change is projected to alter the frequency and magnitude of both floods and droughts. The impact is expected to vary from region to region. The few available studies suggest that flood hazards will increase over more than half of the globe, in particular in central and eastern Siberia, parts of Southeast Asia including India, tropical Africa, and northern South America, but decreases are projected in parts of northern and Eastern Europe, Anatolia, central and East Asia, central North America, and southern South America (*limited evidence*, *high agreement*).The frequency of floods in small river basins is *very likely* to increase, but that may not be true of larger watersheds because intense rain is usually confined to more limited areas. Spring snowmelt floods are *likely* to become smaller, both because less winter precipitation will fall as snow and because more snow will melt during thaws over the course of the entire winter. Worldwide, the damage from floods will increase because more people and more assets will be in harm's way.

By the end of the 21st century meteorological droughts (less rainfall) and agricultural droughts (drier soil) are projected to become longer, or more frequent, or both, in some regions and some seasons, because of reduced rainfall or increased evaporation or both. But it is still uncertain what these rainfall and soil moisture deficits might mean for prolonged reductions of streamflow and lake and groundwater levels. Droughts are projected to intensify in southern Europe and the Mediterranean region, central Europe, central and southern North America, Central America, northeast Brazil, and southern Africa. In dry regions, more intense droughts will stress water supply systems. In wetter regions, more intense seasonal droughts can be managed by current water supply systems and by adaptation; for example, demand can be reduced by using water more efficiently, or supply can be increased by increasing the storage capacity in reservoirs.

headwater basin of the Ganges River, increased precipitation and glacier runoff are projected to increase sediment yield by 26% by 2050 (Neupane and White, 2010). In the tropics, the intensity of cyclones is projected to increase 2 to 11% by 2100, which may increase soil erosion and landslides (Knutson et al., 2010).

In summary, projected increases in heavy rainfall and temperature will lead to changes in soil erosion and sediment load, but owing to the nonlinear dependence of soil erosion on rainfall rate and its strong dependence on land cover there is *low confidence* in projected changes in erosion rates. At the end of the 21st century, the impact of climate change on soil erosion is expected to be twice the impact of land use change (Yang et al., 2003), although management practices may mitigate the problem at catchment scale.

3.4.8. Extreme Hydrological Events (Floods and Droughts)

The *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX; Seneviratne et al., 2012) recognized that projected increases in temperature and heavy precipitation imply regional-scale changes in flood frequency and intensity, but with *low confidence* because these projections were obtained from a single GCM. Global flood projections based on multiple CMIP5 GCM simulations coupled with global hydrology and land surface models (Dankers et al., 2013; Hirabayashi et al., 2013) show flood hazards increasing over about half of the globe, but with great variability at the catchment scale. Projections of increased flood hazard are consistent for parts of south and Southeast Asia, tropical Africa, northeast Eurasia, and South America (Figure 3-6), while decreases are projected in parts of northern and Eastern Europe, Anatolia, central Asia, central North America, and southern South America. This spatial pattern resembles closely that described by Seneviratne et al. (2012), but the latest projections justify *medium confidence* despite new appreciation of the large uncertainty owing to variation between climate models and their coupling to hydrological models.

There have been several assessments of the potential effect of climate change on meteorological droughts (less rainfall) and agricultural droughts (drier soil) (e.g., WGI AR5 Chapter 12; Vidal et al., 2012; Orlowsky and Seneviratne, 2013), but few on hydrological droughts, either in terms of river runoff or groundwater levels. Many catchment-scale studies (Section 3.4.4) consider changes in indicators of low river flow (such as the flow exceeded 95% of the time), but these indicators do not necessarily characterize "drought" as they define neither duration nor spatial extent, and are not necessarily particularly extreme or rare. In an ensemble comparison under SRES A1B of the proportion of the land surface exhibiting significant projected changes in hydrological drought frequency to the proportions exhibiting significant changes in meteorological and agricultural drought frequency, 18 to 30% of the land surface (excluding cold areas) experienced a significant increase in the frequency of 3-month hydrological droughts, while about 15 to 45% saw a decrease (Taylor I. et al., 2013). This is a smaller area with increased frequency, and a larger area with decreased frequency, than for meteorological and agricultural droughts, and is understandable because river flows reflect the accumulation of rainfall over time. Flows during dry periods may be sustained by earlier rainfall. For example, at the catchment scale in the Pacific Northwest (Jung and Chang, 2012),

(a)

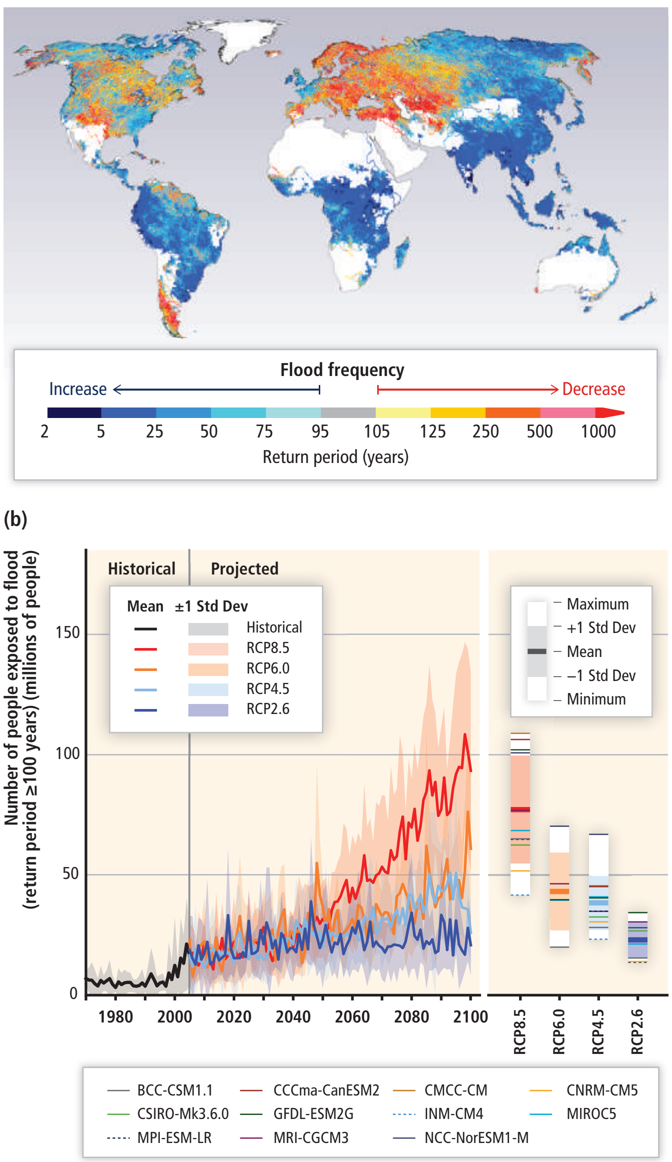


Figure 3-6 | (a) Multi-model median return period (years) in the 2080s for the 20th century 100-year flood (Hirabayashi et al., 2013), based on one hydrological model driven by 11 Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCMs) under Representative Concentration Pathway 8.5 (RCP8.5). At each location the magnitude of the 100-year flood was estimated by fitting a Gumbel distribution function to time series of simulated annual maximum daily discharge in 1971–2000, and the return period of that flood in 2071–2100 was estimated by fitting the same distribution to discharges simulated for that period. Regions with mean runoff less than 0.01 mm day^{-1}, Antarctica, Greenland, and Small Islands are excluded from the analysis and indicated in white. (b) Global exposure to the 20th-century 100-year flood (or greater) in millions of people (Hirabayashi et al., 2013). Left: Ensemble means of historical (black thick line) and future simulations (colored thick lines) for each scenario. Shading denotes ±1 standard deviation. Right: Maximum and minimum (extent of white), mean (thick colored lines), ±1 standard deviation (extent of shading), and projections of each GCM (thin colored lines) averaged over the 21st century. The impact of 21st century climate change is emphasized by fixing the population to that of 2005. Annual global flood exposure increases over the century by 4 to 14 times as compared to the 20th century (4 ± 3 (RCP2.6), 7 ± 5 (RCP4.5), 7 ± 6 (RCP6.0), and 14 ± 10 (RCP8.5) times, or 0.1% to 0.4 to 1.2% of the global population in 2005). Under a scenario of moderate population growth (UN, 2011), the global number of exposed people is projected to increase by a factor of 7 to 25, depending on the RCP, with strong increases in Asia and Africa due to high population growth.

short hydrological droughts are projected to increase in frequency while longer droughts remain unchanged because, although dry spells last longer, winter rainfall increases.

The impacts of floods and droughts are projected to increase even when the hazard remains constant, owing to increased exposure and vulnerability (Kundzewicz et al., 2013). Projected flood damages vary greatly between models and from region to region, with the largest losses in Asia. Studies of projected flood damages are mainly focused in Europe, the USA, and Australia (Handmer et al., 2012; Bouwer, 2013). In Europe, the annual damage (€6.4 billion) and number of people exposed (200,000) in 1961–1990 are expected to increase about twofold by the 2080s under scenario B2 and about three times under scenario A2 (Feyen et al., 2012). Drought impacts at continental and smaller scales are difficult to assess because they will vary greatly with the local hydrological setting and water management practices (Handmer et al., 2012). More frequent droughts due to climate change may challenge existing water management systems (Kim et al., 2009); together with an increase of population, this may place at risk even the domestic supply in parts of Africa (MacDonald et al., 2009).

3.5. Projected Impacts, Vulnerabilities, and Risks

In general, projections of freshwater-related impacts, vulnerabilities, and risks caused by climate change are evaluated by comparison to historical conditions. Such projections are helpful for understanding human impact on nature and for supporting adaptation to climate change. However, for supporting decisions on climate mitigation, it is more helpful to compare the different hydrological changes that are projected under different future GHG emissions scenarios, or different amounts of global mean temperature rise. One objective of such projections is to quantify what may happen under current water resources management practice, and another is to indicate what actions may be needed to avoid undesirable outcomes (Oki and Kanae, 2006). The studies compiled in Table 3-2 illustrate the benefits of reducing GHG emissions for the Earth's freshwater systems. Emissions scenarios are rather similar until the 2050s. Their impacts, and thus the benefits of mitigation, tend to become more clearly marked by the end of the 21st century. For example, the fraction of the world population exposed to a 20th century 100-year flood is projected to be, at the end of the 21st century, three times higher per year for RCP8.5 than for RCP2.6 (Hirabayashi et al., 2013). Each degree of global warming (up to 2.7°C above preindustrial levels; Schewe et al., 2013) is projected to decrease renewable water resources by at least 20% for an additional 7% of the world population. The number of people with significantly decreased access to renewable groundwater resources is projected to be roughly 50% higher under RCP8.5 than under RCP2.6 (Portmann et al., 2013). The percentage of global population living in river basins with new or aggravated water scarcity is projected to increase with global warming, from 8% at 2°C to 13% at 5°C (Gerten et al., 2013).

3.5.1. Availability of Water Resources

About 80% of the world's population already suffers serious threats to its water security, as measured by indicators including water availability,

Table 3-2 | Effects of different greenhouse gas (GHG) emissions scenarios on hydrological changes and freshwater-related impacts of climate change on humans and ecosystems. Among the Special Report on Emission Scenarios (SRES) scenarios, GHG emissions are highest in A1f and A2, lower in A1 and B2, and lowest in B1. Representative Concentration Pathway 8.5 (RCP8.5) is similar to A2, while the lower emissions scenarios RCP6.0 and RCP4.5 are similar to B1. RCP2.6 is a very low emissions scenario (Figure 1-4 and Section 1.1.3.1 in Chapter 1). The studies in the table give global warming (GW: global mean temperature rise, quantified as the Coupled Model Intercomparison Project Phase 5 (CMIP5) model mean) over different reference periods, typically since pre-industrial. GW since pre-industrial is projected to be, for RCP8.5, approximately 2°C in the 2040s and 4°C in the 2090s. For RCP6.0, GW is 2°C in the 2060s and 2.5°C in the 2090s, while in RCP2.6, GW stays below 1.5°C throughout the 21st century (Figure 1-4 in Chapter 1). Population scenario SSP2 assumes a medium population increase. The number of GCMs that were used in the studies is provided.

Type of hydrological change or impact	Description of indicator	Hydrological change or impact in different emissions scenarios or for different degrees of global warming (GW)	Reference
Decrease of renewable water resources, global scale	Percent of global population affected by a water resource decrease of more than 20% as compared to the 1990s (mean of 5 General Circulation Models (GCMs) and 11 global hydrological models, population scenario SSP2)	Up to 2°C above the 1990s (GW 2.7°C), each degree of GW affects an additional 7%	Schewe et al. (2013)
Decrease of renewable groundwater resources, global scale	Percent of global population affected by a groundwater resource decrease of more than 10% by the 2080s as compared to the 1980s (mean and range of 5 GCMs, population scenario SSP2)	• RCP2.6: 24% (11–39%) • RCP4.5: 26% (23–32%) • RCP6.0: 32% (18–45%) • RCP8.5: 38% (27–50%)	Portmann et al. (2013)
Exposure to floods, global scale	Percent of global population annually exposed, in the 2080s, to a flood corresponding to the 100-year flood discharge for the 1980s (mean and range of 5–11 GCMs, population constant at 2005 values)	• RCP2.6: 0.4% (0.2–0.5%) • RCP4.5: 0.6% (0.4–1.0%) • RCP6.0: 0.7% (0.3–1.1%) • RCP8.5: 1.2% (0.6–1.7%) • GW 2°C: 0.5% (0.3–0.6%) • GW 4°C: 1.2% (0.8–2.2%) • 1980s: 0.1% (0.04–0.16%)	Hirabayashi et al. (2013)
Change in irrigation water demand, global scale	Change of required irrigation water withdrawals by the 2080s (on area irrigated around 2000) as compared to the 1980s (range of 3 GCMs)	• RCP2.6: –0.2 to 1.6% • RCP4.5: 1.9–2.8% • RCP8.5: 6.7–10.0%	Hanasaki et al. (2013)
River flow regime shifts from perennial to intermittent and vice versa, global scale	Percent of global land area (except Greenland and Antarctica) affected by regime shifts between the 1970s and the 2050s (range of 2 GCMs)	• SRES B2: 5.4–6.7% • SRES A2: 6.3–7.0%	Döll and Müller Schmied (2012)
Water scarcity	Percent of global population living in countries with less than 1300 $m^3 yr^{-1}$ of per capita blue water resources in the 2080s (mean of 17 GCMs, population constant at 2000 values)	No significant differences between SRES B1 and A2	Gerten et al. (2011)
New or aggravated water scarcity	Percent of global population living in river basins with new or aggravated water scarcity around 2100 as compared to 2000 (less than 1000 $m^3 yr^{-1}$ of per capita blue water resources) (median of 19 GCMs, population constant at 2000 values)	• GW 2°C: 8% • GW 3.5°C: 11% • GW 5°C: 13%	Gerten et al. (2013)
Exposure to water scarcity	Population in water-stressed watersheds (less than 1000 $m^3 yr^{-1}$ of per capita blue water resources) exposed to an increase in stress (1 GCM)	For emissions scenarios with 2°C target, compared to SRES A1: • 5–8% impact reduction in 2050 • 10–20% reduction in 2100	Arnell et al. (2013)
Change of groundwater recharge in the whole of Australia	Probability that groundwater recharge decreases to less than 50% of the 1990s value by 2050 (16 GCMs)	• GW 1.4°C: close to 0 almost everywhere • GW 2.8°C: in western Australia 0.2–0.6, in central Australia 0.2–0.3, elsewhere close to 1	Crosbie et al. (2013a)
Change in groundwater recharge in East Anglia, UK	Percent change between baseline and future groundwater recharge, in %, by the 2050s (1 GCM)	• SRES B1: –22% • SRES A1f: –26%	Holman et al. (2009)
Change of river discharge, groundwater recharge, and hydraulic head in groundwater in two regions of Denmark	Changes between the 1970s and the 2080s (1 regional climate model)	Differences between SRES B2 and A2 are very small compared to the changes between the 1970s and the 2080s in each scenario.	van Roosmalen et al. (2007)
River flow regime shift for river in Uganda	Shift from bimodal to unimodal (1 GCM)	Occurs in scenarios with GW of at least 4.3°C but not for smaller GW.	Kingston and Taylor (2010)
Agricultural (soil moisture) droughts in France	Mean duration, affected area, and magnitude of short and long drought events throughout the 21st century (1 GCM)	Smaller increases over time for SRES B1 than for A2 and A1B.	Vidal et al. (2012)
Salinization of artificial coastal freshwater lake IJsselmeer in the Netherlands (a drinking water source) due to seawater intrusion	(1) Daily probability of exceedance of maximum allowable concentration (MAC) of chloride (150 mg L^{-1}) (2) Maximum duration of MAC exceedance (2050, 1 GCM)	• Reference period 1997–2007 (GW 0.8°C): (1) 2.5%, (2) 103 days • GW 1.8°C, no change in atmospheric circulation: (1) 3.1%, (2) 124 days • GW 2.8°C and change in atmospheric circulation: (1) 14.3%, (2) 178 days	Bonte and Zwolsman (2010)
Decrease of hydropower production at Lake Nasser, Egypt	Reduction of mean annual hydropower production by the 2080s compared to hydropower production 1950–99 (11 GCMs)	• SRES B1: 8% • SRES A2: 7%	Beyene et al. (2010)
Reduction of usable capacity of thermal power plants in Europe and USA due to low river flow and excessive water temperature	Number of days per year with a capacity reduction of more than 50% (for existing power plants) (2031–2060, 3 GCMs)	• Without climate change: 16 • SRES B1: 22 • SRES A2: 24	van Vliet et al. (2012)
Flood damages in Europe (EU27)	(1) Expected annual damages, in 2006 (2) Expected annual population exposed (2080s, 2 GCMs)	• SRES B2: (1) 14–15 billion € yr^{-1}, (2) 440,000–470,000 people • SRES A2: (1) 18–21 billion € yr^{-1}, (2) 510,000–590,000 people • Reference period: (1) 6.4 billion € yr^{-1}, (2) 200,000 people	Feyen et al. (2012)

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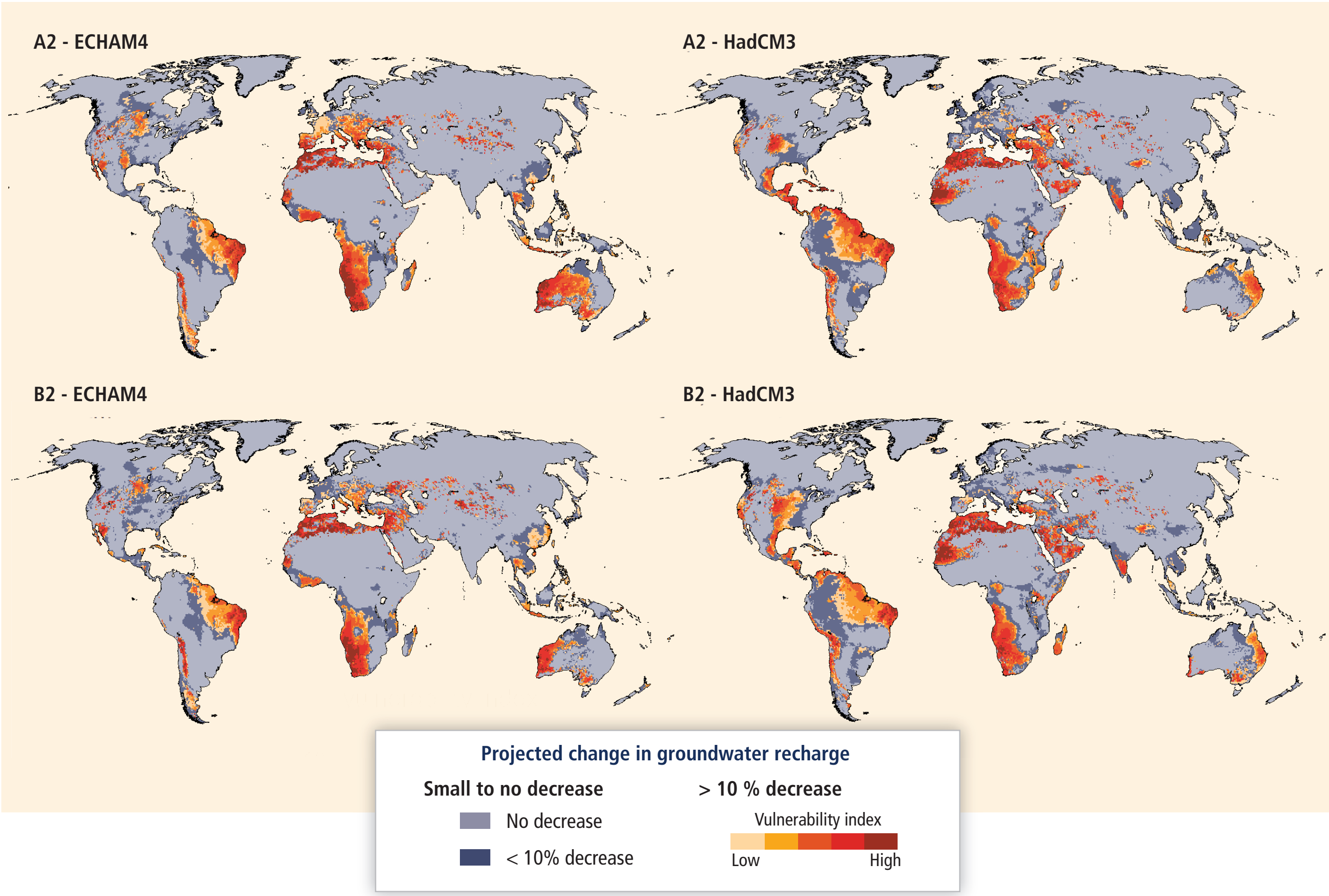


Figure 3-7 | Human vulnerability to climate change–induced decreases of renewable groundwater resources by the 2050s. Lower (Special Report on Emission Scenarios (SRES) B2) and higher (SRES A2) emissions pathways are interpreted by two global climate models. The higher the vulnerability index (computed by multiplying percentage decrease of groundwater recharge by a sensitivity index), the higher is the vulnerability. The index is defined only for areas where groundwater recharge is projected to decrease by at least 10% relative to 1961–1990 (Döll, 2009).

water demand, and pollution (Vörösmarty et al., 2010). Climate change can alter the availability of water and therefore threaten water security as defined by UNESCO (2011).

Global-scale analyses so far have concentrated on measures of resource availability rather than the multi-dimensional indices used in Vörösmarty et al. (2010). All have simulated future river flows or groundwater recharge using global-scale hydrological models. Some have assessed future availability based on runoff per capita (Hayashi et al., 2010; Arnell et al., 2011, 2013; Fung et al., 2011; Murray et al., 2012; Gerten et al., 2013; Gosling and Arnell, 2013; Schewe et al., 2013), whilst others have projected future human withdrawals and characterized availability by the ratio of withdrawals to availability from runoff or recharge (Arnell et al., 2011; Gosling and Arnell, 2013; Hanasaki et al., 2013). A groundwater vulnerability index was constructed that combined future reductions of renewable groundwater resources with water scarcity, dependence on groundwater, and the Human Development Index (Figure 3-7) (Döll, 2009). There are several key conclusions from this set of studies. First, the spatial distribution of the impacts of climate change on resource availability varies considerably between climate models, and strongly with the pattern of projected rainfall change. There is strong consistency in projections of reduced availability around the Mediterranean and parts of southern Africa, but much greater variation in projections for south and East Asia. Second, some water-stressed areas see increased runoff in the future (Section 3.4.4), and therefore less exposure to water resources stress. Third, over the next few decades and for increases in global mean temperature of less than around 2°C above preindustrial, changes in population will generally have a greater effect on changes in resource availability than will climate change. Climate change would, however, regionally exacerbate or offset the effects of population pressures. Fourth, estimates of future water availability are sensitive not only to climate and population projections and population assumptions, but also to the choice of hydrological impact model (Schewe et al., 2013) and to the adopted measure of stress or scarcity. As an indication of the potential magnitude of the impact of climate change, Schewe et al. (2013) estimated that about 8% of the global population would see a severe reduction in water resources (a reduction in runoff either greater than 20% or more than the standard deviation of current annual runoff) with a 1°C rise in global mean temperature (compared to the 1990s), rising to 14% at 2°C and 17% at 3°C; the spread across climate and hydrological models was, however, large.

Under climate change, reliable surface water supply is expected to decrease due to increased variability of river flow that is due in turn to

Frequently Asked Questions

FAQ 3.2 | How will the availability of water resources be affected by climate change?

Climate models project decreases of renewable water resources in some regions and increases in others, albeit with large uncertainty in many places. Broadly, water resources are projected to decrease in many mid-latitude and dry subtropical regions, and to increase at high latitudes and in many humid mid-latitude regions (*high agreement*, *robust evidence*). Even where increases are projected, there can be short-term shortages due to more variable streamflow (because of greater variability of precipitation) and seasonal reductions of water supply due to reduced snow and ice storage. Availability of clean water can also be reduced by negative impacts of climate change on water quality; for instance, the quality of lakes used for water supply could be impaired by the presence of algae-producing toxins.

increased precipitation variability and decreased snow and ice storage. Under these circumstances, it might be beneficial to take advantage of the storage capacity of groundwater and to increase groundwater withdrawals (Kundzewicz and Döll, 2009). However, this option is sustainable only where, over the long term, withdrawals remain well below recharge, while care must also be taken to avoid excessive reduction of groundwater outflow to rivers. Therefore, groundwater cannot be expected to ease freshwater stress where climate change is projected to decrease groundwater recharge and thus renewable groundwater resources (Kundzewicz and Döll, 2009). The percentage of projected global population (SSP2 population scenario) that will suffer from a decrease of renewable groundwater resources of more than 10% between the 1980s and the 2080s was computed to range from 24% (mean based on five GCMs, range 11 to 39%) for RCP2.6 to 38% (range 27 to 50%) for RCP8.5 (Portmann et al., 2013; see also Table 3-2). The land area affected by decreases of groundwater resources increases linearly with global mean temperature rise between 0°C and 3°C. For each degree of global mean temperature rise, an additional 4% of the global land area is projected to suffer a groundwater resources decrease of more than 30%, and an additional 1% to suffer a decrease of more than 70% (Portmann et al., 2013).

3.5.2. Water Uses

3.5.2.1. Agriculture

Water demand and use for food and livestock feed production is governed not only by crop management and its efficiency, but also by the balance between atmospheric moisture deficit and soil water supply. Thus, changes in climate (precipitation, temperature, radiation) will affect the water demand of crops grown in both irrigated and rainfed systems. Using projections from 19 CMIP3 GCMs forced by SRES A2 emissions to drive a global vegetation and hydrology model, climate change by the 2080s would hardly alter the global irrigation water demand of major crops in areas currently equipped for irrigation (Konzmann et al., 2013). However, there is *high confidence* that irrigation demand will increase significantly in many areas (by more than 40% across Europe, USA, and parts of Asia). Other regions—including major irrigated areas in India, Pakistan, and southeastern China—might experience a slight decrease in irrigation demand, due for example to higher precipitation, but only under some climate change scenarios (also see Biemans et al., 2013). Using seven global hydrological models but a limited set of CMIP5 projections, Wada et al. (2013) suggested a global increase in irrigation demand by the 2080s (ensemble average 7 to 21% depending on emissions scenario), with a pronounced regional pattern, a large inter-model spread, and possible seasonal shifts in crop water demand and consumption. By contrast, based on projections from two GCMs and two emissions scenarios, a slight global decrease in crop water deficits was suggested in both irrigated and rainfed areas by the 2080s, which can be explained partly by a smaller difference between daily maximum and minimum temperatures (Zhang and Cai, 2013). As in other studies, region-to-region variations were very heterogeneous.

Where poor soil is not a limiting factor, physiological and structural crop responses to elevated atmospheric CO_2 concentration (CO_2 fertilization) might partly cancel out the adverse effects of climate change, potentially reducing global irrigation water demand (Konzmann et al., 2013; see also Box CC-VW). However, even in this optimistic case, increases in irrigation water demand by >20% are still projected under most scenarios for some regions, such as southern Europe. In general, future irrigation demand is projected to exceed local water availability in many places (Wada et al., 2013). The water demand to produce a given amount of food on either irrigated or rainfed cropland will increase in many regions due to climate change alone (Gerten et al., 2011, projections from 17 CMIP3 GCMs, SRES A2 emissions), but this increase might be moderated by concurrent increases in crop water productivity due to CO_2 effects, that is, decreases in per-calorie water demand. The CO_2 effects may thus lessen the global number of people suffering water scarcity; nonetheless, the effect of anticipated population growth is *likely* to exceed those of climate and CO_2 change on agricultural water demand, use, and scarcity (Gerten et al., 2011).

Rainfed agriculture is vulnerable to increasing precipitation variability. Differences in yield and yield variability between rainfed and irrigated land may increase with changes in climate and its variability (e.g., Finger et al., 2011). Less irrigation water might be required for paddy rice cultivation in monsoon regions where rainfall is projected to increase and the crop growth period to become shorter (Yoo et al., 2013). Water demand for rainfed crops could be reduced by better management (Brauman et al., 2013), but unmitigated climate change may counteract such efforts, as shown in a global modeling study (Rost et al., 2009). In some regions, expansion of irrigated areas or increases of irrigation efficiencies may overcome climate change impacts on agricultural water demand and use (McDonald and Girvetz, 2013).

3.5.2.2. Energy Production

Hydroelectric and thermal power plants, and the irrigation of bioenergy crops (Box CC-WE), require large amounts of water. This section assesses the impact of hydrological changes (as described in Section 3.4) on hydroelectric and thermal power production. The impacts of changes in energy production due to climate change mitigation efforts are discussed in Section 3.7.2.1, while the economic implications of the impact of climate change on thermal power and hydropower production as well as adaptation options are assessed in Chapter 10.

Climate change affects hydropower generation through changes in the mean annual streamflow, shifts of seasonal flows, and increases of streamflow variability (including floods and droughts), as well as by increased evaporation from reservoirs and changes in sediment fluxes. Therefore, the impact of climate change on a specific hydropower plant will depend on the local change of these hydrological characteristics, as well as on the type of hydropower plant and on the (seasonal) energy demand, which will itself be affected by climate change (Golombek et al., 2012). Run-of-river power plants are more susceptible to increased flow variability than plants at dams. Projections of future hydropower generation are subject to the uncertainty of projected precipitation and streamflow. For example, projections to the 2080s of hydropower generation in the Pacific Northwest of the USA range from a decrease of 25% to an increase of 10% depending on the climate model (Markoff and Cullen, 2008). Based on an ensemble of 11 GCMs, hydropower generation at the Aswan High Dam (Egypt) was computed to remain constant until the 2050s but to decrease, following the downward trend of mean annual river discharge, to 90% (ensemble mean) of current mean annual production under both SRES B1 and A2 (Beyene et al., 2010; see also Table 3-2). In snow-dominated basins, increased discharge in winter, smaller and earlier spring floods, and reduced discharge in summer have already been observed (Section 3.2.6) and there is *high confidence* that these trends will continue. In regions with high electricity demands for heating, this makes the annual hydrograph more similar to seasonal variations in electricity demand, reducing required reservoir capacities and providing opportunities for operating dams and power stations to the benefit of riverine ecosystems (Renofalt et al., 2010; Golombek et al., 2012). In regions with high electricity demand for summertime cooling, however, this seasonal streamflow shift is detrimental. In general, climate change requires adaptation of operating rules (Minville et al., 2009; Raje and Mujumdar, 2010) which may, however, be constrained by reservoir capacity. In California, for example, high-elevation hydropower systems with little storage, which rely on storage in the snowpack, are projected to yield less hydropower owing to the increased occurrence of spills, unless precipitation increases significantly (Madani and Lund, 2010). Storage capacity expansion would help increase hydropower generation but might not be cost effective (Madani and Lund, 2010).

Regarding water availability for cooling of thermal power plants, the number of days with a reduced useable capacity is projected to increase in Europe and the USA, owing to increases in stream temperatures and the incidence of low flows (Flörke et al., 2012; van Vliet et al., 2012; see also Table 3-2). Warmer cooling water was computed to lower thermal power plant efficiency and thus electricity production by 1.5 to 3% in European countries by the 2080s under emissions scenario SRES A1B (Golombek et al., 2012).

3.5.2.3. Municipal Services

Under climate change, water utilities are confronted by the following (Bates et al., 2008; Jiménez, 2008; van Vliet and Zwolsman, 2008; Black and King, 2009; Brooks et al., 2009; Whitehead et al., 2009a; Bonte and Zwolsman, 2010; Hall and Murphy, 2010; Mukhopadhyay and Dutta, 2010; Qin et al., 2010; Chakraborti et al., 2011; Major et al., 2011; Thorne and Fenner, 2011; Christierson et al., 2012):

- Higher ambient temperatures, which reduce snow and ice volumes and increase the evaporation rate from lakes, reservoirs, and aquifers. These changes decrease natural storage of water, and hence, unless precipitation increases, its availability. Moreover, higher ambient temperatures increase water demand, and with it the competition for the resource (*medium* to *high agreement*, *limited evidence*).
- Shifts in timing of river flows and possible more frequent or intense droughts, which increase the need for artificial water storage.
- Higher water temperatures, which encourage algal blooms and increase risks from cyanotoxins and natural organic matter in water sources, requiring additional or new treatment of drinking water (*high agreement*, *medium evidence*). On the positive side, biological water and wastewater treatment is more efficient when the water is warmer (Tchobanoglous et al., 2003).
- Possibly drier conditions, which increase pollutant concentrations. This is a concern especially for groundwater sources that are already of low quality, even when pollution is natural as in India and Bangladesh, North and Latin America and Africa; here arsenic, iron, manganese, and fluorides are often a problem (Black and King, 2009).
- Increased storm runoff, which increases loads of pathogens, nutrients, and suspended sediment.
- Sea level rise, which increases the salinity of coastal aquifers, in particular where groundwater recharge is also expected to decrease.

Climate change also impacts water quality indirectly. For instance, at present many cities rely on water from forested catchments that requires very little treatment. More frequent and severe forest wildfires could seriously degrade water quality (Emelko et al., 2011; Smith et al., 2011).

Many drinking water treatment plants—especially small ones—are not designed to handle the more extreme influent variations that are to be expected under climate change. These demand additional or even different infrastructure capable of operating for up to several months per year, which renders wastewater treatment very costly, notably in rural areas (Zwolsman et al., 2010; Arnell et al., 2011).

Sanitation technologies vary in their resilience to climate impacts (Howard et al., 2010). For sewage, three climatic conditions are of interest (NACWA, 2009; Zwolsman et al., 2010):

- Wet weather: heavier rainstorms mean increased amounts of water and wastewater in combined systems for short periods. Current

3

designs, based on critical "design storms" defined through analysis of historical precipitation data, therefore need to be modified. New strategies to adapt to and mitigate urban floods need to be developed, considering not only climate change but also urban design, land use, the "heat island effect," and topography (Changnon, 1969).
- Dry weather: soil shrinks as it dries, causing water mains and sewers to crack and making them vulnerable to infiltration and exfiltration of water and wastewater. The combined effects of higher temperatures, increased pollutant concentrations, longer retention times, and sedimentation of solids may lead to increasing corrosion of sewers, shorter asset lifetimes, more drinking water pollution, and higher maintenance costs.
- Sea level rise: intrusion of brackish or salty water into sewers necessitates processes that can handle saltier wastewater.

Increased storm runoff implies the need to treat additional wastewater when combined sewers are used, as storm runoff adds to sewage; in addition, the resulting mixture has a higher content of pathogens and pollutants. Under drier conditions higher concentrations of pollutants in wastewater, of any type, are to be expected and must be dealt with (Whitehead et al., 2009a,b; Zwolsman et al., 2010). The cost may rule this out in low-income regions (Chakraborti et al., 2011; Jiménez, 2011). The disposal of wastewater or fecal sludge is a concern that is just beginning to be addressed in the literature (Seidu et al., 2013).

3.5.2.4. Freshwater Ecosystems

Freshwater ecosystems are composed of biota (animals, plants, and other organisms) and their abiotic environment in slow-flowing surface waters such as lakes, man-made reservoirs, or wetlands; in fast-flowing surface waters such as rivers and creeks; and in the groundwater. They have suffered more strongly from human activities than have marine and terrestrial ecosystems. Between 1970 and 2000, populations of freshwater species included in the Living Planet Index declined on average by 50%, compared to 30% for marine and also for terrestrial species (Millennium Ecosystem Assessment, 2005). Climate change is an additional stressor of freshwater ecosystems, which it affects not only through increased water temperatures (discussed in Section 4.3.3.3) but also by altered streamflow regimes, river water levels, and extent and timing of inundation (Box CC-RF). Wetlands in dry environments are hotspots of biological diversity and productivity, and their biotas are at risk of extinction if runoff decreases and the wetland dries out (as described for Mediterranean-type temporary ponds by Zacharias and Zamparas, 2010). Freshwater ecosystems are also affected by water quality changes induced by climate change (Section 3.2.5), and by human adaptations to climate change-induced increases of streamflow variability and flood risk, such as the construction of dykes and dams (Ficke et al., 2007; see also Section 3.7.2).

3.5.2.5. Other Uses

In addition to direct impacts, vulnerabilities, and risks in water-related sectors, indirect impacts of hydrological changes are expected for navigation, transportation, tourism, and urban planning (Pinter et al., 2006; Koetse and Rietveld, 2009; Rabassa, 2009; Badjeck et al., 2010; Beniston, 2012). Social and political problems can result from hydrological changes. For example, water scarcity and water overexploitation may increase the risks of violent conflicts and nation-state instability (Barnett and Adger, 2007; Burke et al. 2009; Buhaug et al., 2010; Hsiang et al., 2011). Snowline rise and glacier shrinkage are *very likely* to impact environmental, hydrological, geomorphological, heritage, and tourism resources in cold regions (Rabassa, 2009), as already observed for tourism in the European Alps (Beniston, 2012). Although most impacts will be adverse, some might be beneficial.

3.6. Adaptation and Managing Risks

In the face of hydrological changes and freshwater-related impacts, vulnerability, and risks due to climate change, there is need for adaptation and for increasing resilience. Managing the changing risks due to the impacts of climate change is the key to adaptation in the water sector (IPCC, 2012), and risk management should be part of decision making and the treatment of uncertainty (ISO, 2009). Even to exploit the positive impacts of climate change on freshwater systems, adaptation is generally required.

Frequently Asked Questions

FAQ 3.3 | How should water management be modified in the face of climate change?

Managers of water utilities and water resources have considerable experience in adapting their policies and practices to the weather. But in the face of climate change, long-term planning (over several decades) is needed for a future that is highly uncertain. A flexible portfolio of solutions that produces benefits regardless of the impacts of climate change ("low-regret" solutions) and that can be implemented adaptively, step by step, is valuable because it allows policies to evolve progressively, thus building on—rather than losing the value of—previous investments. Adaptive measures that may prove particularly effective include rainwater harvesting, conservation tillage, maintaining vegetation cover, planting trees in steeply sloping fields, mini-terracing for soil and moisture conservation, improved pasture management, water reuse, desalination, and more efficient soil and irrigation water management. Restoring and protecting freshwater habitats, and managing natural floodplains, are additional adaptive measures that are not usually part of conventional management practice.

3.6.1. Options

There is growing agreement that an adaptive approach to water management can successfully address uncertainty due to climate change. Although there is *limited evidence* of the effectiveness of such an approach, the evidence is growing (Section 3.6.2). Many practices identified as adaptive were originally reactions to climate variability. Climate change provides many opportunities for "low-regret" solutions, capable of yielding social and/or economic benefits and adaptive both to variability and to change (Table 3-3). Adaptive techniques include scenario planning, experimental approaches that involve learning from experience, and the development of flexible solutions that are resilient to uncertainty. A program of adaptation typically mixes "hard" infrastructural and "soft" institutional measures (Bates et al., 2008; Cooley, 2008; Mertz et al., 2009; Sadoff and Muller, 2009; UNECE, 2009; Olhoff and Schaer, 2010).

To avoid adaptation that goes wrong—"maladaptation"—scientific research results should be analyzed during planning. Low-regret solutions, such as those for which moderate investment clearly increases the capacity to cope with projected risks or for which the investment is justifiable under all or almost all plausible scenarios, should be considered explicitly. Involving all stakeholders, reshaping planning processes, coordinating the management of land and water resources, recognizing linkages between water quantity and quality, using surface water and groundwater conjunctively, and protecting and restoring natural systems are examples of principles that can beneficially inform planning for adaptation (World Bank, 2007).

Integrated Water Resource Management continues to be a promising instrument for exploring adaptation to climate change. It can be joined with a Strategic Environmental Assessment to address broader considerations. Attention is currently increasing to "robust measures" (European Communities, 2009), which are measures that perform well under different future conditions and clearly optimize prevailing strategies (Sigel et al., 2010). Barriers to adaptation are discussed in detail in Section 16.4. Barriers to adaptation in the freshwater sector include lack of human and institutional capacity, lack of financial resources, lack of awareness, and lack of communication (Browning-Aiken et al., 2007; Burton, 2008; Butscher and Huggenberger, 2009; Zwolsman et al., 2010). Institutional structures can be major barriers to adaptation (Goulden et al., 2009; Engle and Lemos, 2010; Huntjens et al., 2010; Stuart-Hill and Schulze, 2010; Ziervogel et al., 2010; Wilby and Vaughan, 2011; Bergsma et al., 2012); structures that promote participation of and collaboration between stakeholders tend to encourage adaptation. Some adaptation measures may not pass the test of workability in an uncertain future (Campbell et al., 2008), and uncertainty (Section 3.6.2) can be another significant barrier.

Case studies of the potential effectiveness of adaptation measures are increasing. Changes in operating practices and infrastructure improvements could help California's water managers respond to changes in the volume and timing of supply (Medellin-Azuara et al., 2008; Connell-Buck et al., 2011). Other studies include evaluations of the effectiveness of different adaptation options in Washington state, USA (Miles et al., 2010) and the Murray-Darling basin, Australia (Pittock and Finlayson, 2011), and of two dike-heightening strategies in the Netherlands (Hoekstra and de Kok, 2008). Such studies have demonstrated that it is technically feasible in general to adapt to projected climate changes, but not all have considered how adaptation would be implemented.

3.6.2. Dealing with Uncertainty in Future Climate Change

One of the key challenges in factoring climate change into water resources management lies in the uncertainty. Some approaches (e.g., in England and Wales; Arnell, 2011) use a small set of climate scenarios to characterize the potential range of impacts on water resources and flooding. Others (e.g., Brekke et al., 2008; Lopez et al., 2009; Christierson et al., 2012; Hall et al., 2012) use very large numbers of scenarios to generate likelihood distributions of indicators of impact for use in risk assessment. However, it has been argued (Hall, 2007; Stainforth et al., 2007; Dessai et al., 2009) that attempts to construct probability distributions of impacts are misguided because of "deep" uncertainty, which arises because analysts do not know, or cannot agree on, how the climate system and water management systems may change, how models represent possible changes, or how to value the desirability of different outcomes. Stainforth et al. (2007) therefore argue that it is impossible in practice to construct robust quantitative probability distributions of climate change impacts, and that climate change uncertainty needs to be represented differently, for example by using fewer plausible scenarios and interpreting the outcomes of scenarios less quantitatively.

Some go further, arguing that climate models are not sufficiently robust or reliable to provide the basis for adaptation (Koutsoyiannis et al., 2008; Anagnostopoulos et al., 2010; Blöschl and Montanari, 2010; Wilby, 2010), because they are frequently biased and do not reproduce the temporal characteristics (specifically the persistence or "memory") often found in hydrological records. It has been argued (Lins and Cohn, 2011; Stakhiv, 2011) that existing water resources planning methods are sufficiently robust to address the effects of climate change. This view of climate model performance has been challenged and is the subject of some debate (Koutsoyiannis et al., 2009, 2011; Huard, 2011); the critique also assumes that adaptation assessment procedures would use only climate scenarios derived directly from climate model simulations.

Addressing uncertainty in practice by quantifying it through some form of risk assessment, however, is only one way of dealing with uncertainty. A large and increasing literature recommends that water managers should move from the traditional "predict and provide" approach toward adaptive water management (Pahl-Wostl, 2007; Pahl-Wostl et al., 2008; Matthews and Wickel, 2009; Mysiak et al., 2009; Huntjens et al., 2012; Short et al., 2012; Gersonius et al., 2013) and the adoption of resilient or "no-regrets" approaches (WWAP, 2009; Henriques and Spraggs, 2011). Approaches that are resilient to uncertainty are not entirely technical (or supply-side), and participation and collaboration amongst all stakeholders are central to adaptive water management. However, although climate change is frequently cited as a key motive, there is very little published guidance on how to implement the adaptive water management approach. Some examples are given in Ludwig et al. (2009). The most comprehensive overview of adaptive water

Table 3-3 | Categories of climate change adaptation options for the management of freshwater resources.

Category	Option	May assist both adaptation and mitigation
Institutional	Support integrated water resources management, including the integrated management of land considering specifically negative and positive impacts of climate change	X
	Promote synergy of water and energy savings and efficient use	X
	Identify "low-regret policies" and build a portfolio of relevant solutions for adaptation	X
	Increase resilience by forming water utility network working teams	
	Build adaptive capacity	
	Improve and share information	X
	Adapt the legal framework to make it instrumental for addressing climate change impacts	X
	Develop financial tools (credit, subsidies, and public investment) for the sustainable management of water, and for considering poverty eradication and equity	
Design and operation	Design and apply decision-making tools that consider uncertainty and fulfill multiple objectives	
	Revise design criteria of water infrastructure to optimize flexibility, redundancy, and robustness	
	Ensure plans and services are robust, adaptable, or modular; give good value; are maintainable; and have long-term benefits, especially in low-income countries	X
	Operate water infrastructure so as to increase resilience to climate change for all users and sectors	
	When and where water resources increase, alter dam operations to allow freshwater ecosystems to benefit	
	Take advantage of hard and soft adaptation measures	X
	Carry out programs to protect water resources in quantity and quality	
	Increase resilience to climate change by diversifying water sources[a] and improving reservoir management	X
	Reduce demand by controlling leaks, implementing water-saving programs, cascading and reusing water	X
	Improve design and operation of sewers, sanitation, and wastewater treatment infrastructure to cope with variations in influent quantity and quality	
	Provide universal sanitation with technology locally adapted, and provide for proper disposal and reintegration of used water into the environment or for its reuse	
Reduce impact of natural disasters	Implement monitoring and early warning systems	
	Develop contingency plans	
	Improve defenses and site selection for key infrastructure that is at risk of floods	
	Design cities and rural settlements to be resilient to floods	
	Seek and secure water from a diversity (spatially and source-type) of sources to reduce impacts of droughts and variability in water availability	
	Promote both the reduction of water demand and the efficient use of water by all users	
	Promote switching to more appropriate crops (drought-resistant, salt-resistant; low water demand)	X
	Plant flood- or drought-resistant crop varieties	
Agricultural irrigation	Improve irrigation efficiency and reduce demand for irrigation water	X
	Reuse wastewater to irrigate crops and use soil for carbon sequestration	X
Industrial use	When selecting alternative sources of energy, assess the need for water	X
	Relocate water-thirsty industries and crops to water-rich areas	
	Implement industrial water efficiency certifications	X

[a]This includes water reuse, rain water harvesting, and desalination, among others.

Sources: Vörösmarty et al. (2000); Marsalek et al. (2006); Mogaka et al. (2006); Dillon and Jiménez (2008); Jiménez and Asano (2008); Keller (2008); McCafferty (2008); McGuckin (2008); Seah (2008); UN-HABITAT (2008); Thöle (2008); Andrews (2009); Bahri (2009); Munasinghe (2009); NACWA (2009); OFWAT (2009); Reiter (2009); Whitehead et al. (2009b); de Graaf and der Brugge (2010); Dembo (2010); Godfrey et al. (2010); Howard et al. (2010); Mackay and Last (2010); Mukhopadhyay and Dutta (2010); OECD (2010); Renofalt et al. (2010); Zwolsman et al. (2010); Arkell (2011a, 2011b); Elliott et al. (2011); Emelko et al. (2011); Jiménez (2011); Kingsford (2011); Major et al. (2011); Sprenger et al. (2011); UNESCO (2011); Wang X. et al. (2011); Bowes et al. (2012).

management that explicitly incorporates climate change and its uncertainty is the three-step framework of the U.S. Water Utilities Climate Alliance (WUCA, 2010): system vulnerability assessment, utility planning using decision-support methods, and decision making and implementation. Planning methods for decision support include classic decision analysis, traditional scenario planning, and robust decision making (Lempert et al., 1996, 2006; Nassopoulos et al., 2012). The latter was applied by the Inland Empire Utilities Agency, supplying water to a region in Southern California (Lempert and Groves, 2010). This led to the refinement of the company's water resource management plan, making it more robust to three particularly challenging aspects of climate change that were identified by the scenario analysis. Another framework, based on risk assessment, is the threshold-scenario framework of Freas et al. (2008).

3.6.3. Costs of Adaptation to Climate Change

Calculating the global cost of adaptation in the water sector is a difficult task and results are highly uncertain. Globally, to maintain water services at non-climate change levels to the year 2030 in more than 200 countries, total adaptation costs for additional infrastructure were estimated as US$531 billion for the SRES A1B scenario (Kirshen, 2007). Including two further costs, for reservoir construction because the best locations have already been taken, and for unmet irrigation demands, total water sector adaptation costs were estimated as US$225 billion, or US$11 billion per year for the SRES A1B scenario (UNFCCC, 2007).

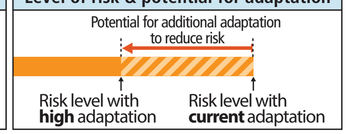
Average annual water supply and flood protection costs to 2050 for restoring service to non-climate change levels were estimated to be US$19.7 billion for a dry GCM projection of the SRES A2 scenario and US$14.4 billion for a wet GCM projection (Ward et al., 2010; World Bank, 2010). Annual urban infrastructure costs, primarily for wastewater treatment and urban drainage, were US$13.0 billion (dry) and US$27.5 billion (wet). Under both GCM projections for the A2 scenario, the water sector accounted for about 50% of total global adaptation cost, which was distributed regionally in the proportions: East Asia/Pacific, 20%; Europe/Central Asia, 10%; Latin America/Caribbean, 20%; Middle East/North Africa, 5%; South Asia, 20%; sub-Saharan Africa, 20%.

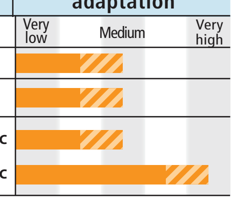
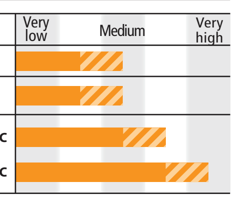
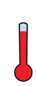
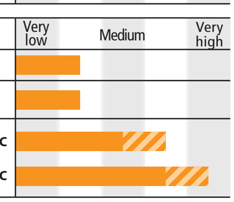
Annual costs for adaptation to climate change in sub-Saharan Africa are estimated as US$1.1 to 2.7 billion for current urban water infrastructure, plus US$1.0 to 2.5 billion for new infrastructure to meet the 2015 Millennium Development Goals (Muller, 2007). These estimates assume a 30% reduction in stream flow and an increase of at least 40% in the unit cost of water. Annual estimates of adaptation costs for urban water storage are US$0.05 to 0.15 billion for existing facilities and US$0.015 to 0.05 billion for new developments. For wastewater treatment, the equivalent estimates are US$0.1 to 0.2 billion and US$0.075 to 0.2 billion.

3.6.4. Adaptation in Practice in the Water Sector

A number of water management agencies are beginning to factor climate change into processes and decisions (Kranz et al., 2010; Krysanova et al., 2010), with the amount of progress strongly influenced by institutional characteristics. Most of the work has involved developing methodologies to be used by water resources and flood managers (e.g., Rudberg et al., 2012), and therefore represents attempts to improve adaptive capacity. In England and Wales, for example, methodologies to gauge the effects of climate change on reliability of water supplies have evolved since the late 1990s (Arnell, 2011), and the strategic plans of water supply companies now generally allow for climate change. Brekke et al. (2009a) describe proposed changes to practices in the USA. Several studies report community-level activities to reduce exposure to current hydrological variability, regarded explicitly as a means of adapting to future climate change (e.g., Barrios et al., 2009; Gujja et al., 2009; Kashaigili et al., 2009; Yu et al., 2009).

Table 3-4 | Key risks from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near term (here assessed over 2030–2040), and longer term (here assessed over 2080–2100). Sources: Xie et al., 2006; Döll, 2009; Kaser et al., 2010; Arnell et al., 2011; Huss, 2011; Jóhannesson et al., 2012; Seneviratne et al., 2012; Arnell and Gosling, 2013; Dankers et al., 2013; Gosling and Arnell, 2013; Hanasaki et al., 2013; Hirabayashi et al., 2013; Kundzewicz et al., 2013; Portmann et al., 2013; Radić et al., 2013; Schewe et al., 2013; WGI AR5 Chapter 13.

Climate-related drivers of impacts			Level of risk & potential for adaptation
 Warming trend	 Drying trend	 Extreme precipitation	

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Flood risks associated with climate change increase with increasing greenhouse gas emissions. (*robust evidence, high agreement*) [3.4.8]	By 2100, the number of people exposed annually to a 20th-century 100-year flood is projected to be three times greater for very high emissions (RCP8.5) than for very low emissions (RCP2.6).		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	 Very low / Medium / Very high
Climate change is projected to reduce renewable water resources significantly in most dry subtropical regions. (*robust evidence, high agreement*) [3.5.1]	This will exacerbate competition for water among agriculture, ecosystems, settlements, industry and energy production, affecting regional water, energy, and food security.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	 Very low / Medium / Very high
Because nearly all glaciers are too large for equilibrium with the present climate, there is a committed water-resources change during much of the 21st century, and changes beyond the committed change are expected due to continued warming; in glacier-fed rivers, total meltwater yields from stored glacier ice will increase in many regions during the next decades but decrease thereafter. (*robust evidence, high agreement*) [3.4.3]	Continued loss of glacier ice implies a shift of peak discharge from summer to spring, except in monsoonal catchments, and possibly a reduction of summer flows in the downstream parts of glacierized catchments.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	 Very low / Medium / Very high

Frequently Asked Questions

FAQ 3.4 | Does climate change imply only bad news about water resources?

There is good news as well as bad about water resources, but the good news is very often ambiguous. Water may become less scarce in regions that get more precipitation, but more precipitation will probably also increase flood risk; it may also raise the groundwater table, which could lead to damage to buildings and other infrastructure or to reduced agricultural productivity due to wet soils or soil salinization. More frequent storms reduce the risk of eutrophication and algal blooms in lakes and estuaries by flushing away nutrients, but increased storm runoff will carry more of those nutrients to the sea, exacerbating eutrophication in marine ecosystems, with possible adverse impacts as discussed in Chapter 30. Water and wastewater treatment yields better results under warmer conditions, as chemical and biological reactions needed for treatment perform in general better at higher temperatures. In many rivers fed by glaciers, there will be a "meltwater dividend" during some part of the 21st century, due to increasing rates of loss of glacier ice, but the continued shrinkage of the glaciers means that after several decades the total amount of meltwater that they yield will begin to decrease (*medium confidence*). An important point is that often impacts do not become "good news" unless investments are made to exploit them. For instance, where additional water is expected to become available, the infrastructure to capture that resource would need to be developed if it is not already in place.

3.7. Linkages with Other Sectors and Services

3.7.1. Impacts of Adaptation in Other Sectors on Freshwater Systems

Adaptation in other sectors such as agriculture, forestry, and industry might have impacts on the freshwater system, and therefore needs to be considered while planning adaptation in the water sector (Jiang et al., 2013). For example, better agricultural land management practices can also reduce erosion and sedimentation in river channels (Lu et al., 2010), while controlled flooding of agricultural land can alleviate the impacts of urban flooding. Increased irrigation upstream may limit water availability downstream (World Bank, 2007). A project designed for other purposes may also deliver increased resilience to climate change as a co-benefit, even without a specifically identified adaptive component (World Bank, 2007; Falloon and Betts, 2010).

3.7.2. Climate Change Mitigation and Freshwater Systems

3.7.2.1. Impact of Climate Change Mitigation on Freshwater Systems

Many measures for climate change mitigation affect freshwater systems. Afforestation generally increases evapotranspiration and decreases total runoff (van Dijk and Keenan, 2007). Afforestation of areas deemed suitable according to the Clean Development Mechanism–Afforestation/Reforestation provisions of the Kyoto Protocol (7.5 million km^2) would lead to large and spatially extensive decreases of long-term average runoff (Trabucco et al., 2008). On 80% of the area, runoff is computed to decline by more than 40%, while on 27% runoff decreases of 80 to 100% were computed, mostly in semiarid areas (Trabucco et al., 2008). For example, economic incentives for carbon sequestration may encourage the expansion of *Pinus radiata* timber plantations in the Fynbos biome of South Africa, with negative consequences for water supply and biodiversity; afforestation is viable to the forestry industry only because it pays less than 1% of the actual cost of streamflow reduction caused by replacing Fynbos by the plantations (Chisholm, 2010). In general, afforestation has beneficial impacts on soil erosion, local flood risk, water quality (nitrogen, phosphorus, suspended sediments), and stream habitat quality (van Dijk and Keenan, 2007; Trabucco et al., 2008; Wilcock et al., 2008).

Irrigated bioenergy crops and hydropower can have negative impacts on freshwater systems (Jacobson, 2009). In the USA, water use for irrigating biofuel crops could increase from 2% of total water consumption in 2005 to 9% in 2030 (King et al., 2010). Irrigating some bioenergy crops may cost more than the energy thus gained. In dry parts of India, pumping from a depth of 60 m for irrigating jatropha is estimated to consume more energy than that gained from the resulting higher crop yields (Gupta et al., 2010). For a biofuel scenario of the International Energy Agency, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030; biofuel production is projected to increase water consumption significantly in some countries (e.g., Germany, Italy, and South Africa), and to exacerbate the already serious water scarcity in others (e.g., Spain and China) (Gerbens-Leenes et al., 2012). Conversion of native Caatinga forest into rainfed fields for biofuels in semiarid northwestern Brazil may lead to a significant increase of groundwater recharge (Montenegro and Ragab, 2010), but there is a risk of soil salinization due to rising groundwater tables.

Hydropower generation leads to alteration of river flow regimes that negatively affect freshwater ecosystems, in particular biodiversity and abundance of riverine organisms (Döll and Zhang, 2010; Poff and Zimmerman, 2010), and to fragmentation of river channels by dams, with negative impacts on migratory species (Bourne et al., 2011). Hydropower operations often lead to discharge changes on hourly timescales that are detrimental to the downstream river ecosystem (Bruno et al., 2009; Zimmerman et al., 2010). However, release management and structural measures like fish ladders can mitigate these negative impacts somewhat (Williams, 2008). In tropical regions, the global warming potential of hydropower, due to methane emissions from man-made reservoirs, may exceed that of thermal power; based on observed emissions of a tropical reservoir, this might be the case where the ratio of hydropower generated to the surface area of the reservoir is less than 1 MW km^{-2} (Gunkel, 2009).

CO_2 leakage to freshwater aquifers from saline aquifers used for carbon capture and storage (CCS) can lower pH by 1 to 2 units and increase concentrations of metals, uranium, and barium (Little and Jackson, 2010). Pressure exerted by gas injection can push brines or brackish water into freshwater parts of the aquifer (Nicot, 2008). Displacement of brine into potable water was not considered in a screening methodology for CCS sites in the Netherlands (Ramírez et al., 2010). Another emergent freshwater-related risk of climate mitigation is increased natural gas extraction from low-permeability rocks. The required hydraulic fracturing process ("fracking") uses large amounts of water (a total of about 9000 to 30,000 m^3 per well, mixed with a number of chemicals), of which a part returns to the surface (Rozell and Reaven, 2012). Fracking is suspected to lead to pollution of the overlying freshwater aquifer or surface waters, but appropriate observations and peer-reviewed studies are still lacking (Jackson et al., 2013). Densification of urban areas to reduce traffic emissions is in conflict with providing additional open space for inundation in case of floods (Hamin and Gurran, 2009).

3.7.2.2. Impact of Water Management on Climate Change Mitigation

A number of water management decisions affect GHG emissions. Water demand management has a significant impact on energy consumption because energy is required to pump and treat water, to heat it, and to treat wastewater. For example, water supply and water treatment were responsible for 1.4% of total electricity consumption in Japan in 2008 (MLIT, 2011). In the USA, total water-related energy consumption was equivalent to 13% of total electricity production in 2005, with 70% for water heating, 14% for wastewater treatment, and only 5% for pumping of irrigation water (Griffiths-Sattenspiel and Wilson, 2009). In China, where agriculture accounts for 62% of water withdrawals, groundwater pumping for irrigation accounted for only 0.6% of China's GHG emissions in 2006, a small fraction of the 17 to 20% share of agriculture as a whole (Wang et al., 2012). Where climate change reduces water resources in dry regions, desalination of seawater as an adaptation option is expected to increase GHG emissions if carbon-based fuels are used as energy source (McEvoy and Wilder, 2012).

In Southeast Asia, emissions due to peatland drainage contribute 1.3 to 3.1% of current global CO_2 emissions from the combustion of fossil fuels (Hooijer et al., 2010), and peatland rewetting could substantially reduce net GHG emissions (Couwenberg et al., 2010). Climate change mitigation by conservation of wetlands will also benefit water quality and biodiversity (House et al., 2010). Irrigation can increase CO_2 storage in soils by reducing water stress and so enhancing biomass production. Irrigation in semiarid California did not significantly increase soil organic carbon (Wu et al., 2008). Water management in rice paddies can reduce methane (CH_4) emissions. If rice paddies are drained at least once during the growing season, with resulting increased water withdrawals, global CH_4 emissions from rice fields could be decreased by 4.1 Tg yr^{-1} (16% around the year 2000), and nitrous oxide (N_2O) emissions would not increase significantly (Yan et al., 2009).

3.8. Research and Data Gaps

Precipitation and river discharge are systematically observed, but data records are unevenly available and unevenly distributed geographically. Information on many other relevant variables, such as soil moisture, snow depth, groundwater depth, and water quality, is particularly limited in developing countries. Relevant socioeconomic data, such as rates of surface water and groundwater withdrawal by each sector, and information on already implemented adaptations for stabilizing water supply, such as long-range diversions, are limited even in developed countries. In consequence, assessment capability is limited in general, and especially so in developing countries.

Modeling studies have shown that the adaptation of vegetation to changing climate may have large impacts on the partitioning of precipitation into evapotranspiration and runoff. This feedback should be investigated more thoroughly (see Box CC-VW).

Relatively little is known about the economic aspects of climate change impacts and adaptation options related to water resources. For example, regional damage curves need to be developed, relating the magnitudes of major water related disasters (such as intense precipitation and surface soil dryness) to the expected costs.

There is a continuing, although narrowing, mismatch between the large scales resolved by climate models and the catchment scale at which water is managed and adaptations must be implemented. Improving the spatial resolution of regional and global climate models, and the accuracy of methods for downscaling their outputs, can produce information more relevant to water management, although the robustness of regional climate projections is still constrained by the realism of GCM simulations of large-scale drivers. More computing capacity is needed to address these problems with more ensemble simulations at high spatial resolution. More research is also needed into novel ways of combining different approaches to projection of plausible changes in relevant climate variables so as to provide robust information to water managers. Robust attribution to anthropogenic climate change of hydrological changes, particularly changes in the frequency of extreme events, is similarly demanding, and further study is required to develop rigorous attribution tools that require less computation. In addition, there is a difficulty to model and interpret results obtained from applying models at different scales and with different logics to follow the future changes on water quality. Moreover, the establishment of a proper baseline to isolate the effects derived from climate change from the anthropogenic cause is a major challenge.

Interactions among socio-ecological systems are not yet well considered in most impact assessments. Particularly, there are few studies on the impacts of mitigation and adaptation in other sectors on the water sector, and conversely. A valuable advance would be to couple hydrological models, or even the land surface components of climate models, to data on water management activities such as reservoir operations, irrigation, and urban withdrawals from surface water or groundwater.

To support adaptation by increasing reliance on groundwater and on the coordinated and combined use of groundwater and surface water, ground-based data are needed in the form of a long-term program to monitor groundwater dynamics and stored groundwater volumes. Understanding of groundwater recharge and groundwater surface water interactions, particularly by the assessment of experiences of conjunctive use of groundwater and surface water, needs to be better developed.

More studies are needed, especially in developing countries, on the impacts of climate change on water quality, and of vulnerability to and ways of adapting to those impacts.

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4 Terrestrial and Inland Water Systems

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Executive Summary

The planet's biota and ecosystem processes were strongly affected by past climate changes at rates of climate change lower than those projected during the 21st century under high warming scenarios (e.g., Representative Concentration Pathway 8.5 (RCP8.5)) (*high confidence*). Most ecosystems are vulnerable to climate change even at rates of climate change projected under low- to medium-range warming scenarios (e.g., RCP2.6 to RCP6.0). The paleoecological record shows that global climate changes comparable in magnitudes to those projected for the 21st century under all scenarios resulted in large-scale biome shifts and changes in community composition; and that for rates projected under RCP6 and 8.5 were associated with species extinctions in some groups (*high confidence*). {4.2.3}

Climate change is projected to be a powerful stressor on terrestrial and freshwater ecosystems in the second half of the 21st century, especially under high-warming scenarios such as RCP6.0 and RCP8.5 (*high confidence*). Direct human impacts such as land use and land use change, pollution, and water resource development will continue to dominate the threats to most freshwater (*high confidence*) and terrestrial (*medium confidence*) ecosystems globally over the next 3 decades. Changing climate exacerbates other impacts on biodiversity (*high confidence*). Ecosystem changes resulting from climate change may not be fully apparent for several decades, owing to long response times in ecological systems (*medium confidence*). Model-based projections imply that under low to moderate warming scenarios (e.g., RCP2.6 to RCP6.0), direct land cover change will continue to dominate over (and conceal) climate-induced change as a driver of ecosystem change at the global scale; for higher climate change scenarios, some model projections imply climate-driven ecosystem changes sufficiently extensive to equal or exceed direct human impacts at the global scale (*medium confidence*). In high-altitude and high-latitude freshwater and terrestrial ecosystems, climate changes exceeding those projected under RCP2.6 will lead to major changes in species distributions and ecosystem function, especially in the second half of the 21st century (*high confidence*). {4.2.4, 4.3.2.5, 4.3.3, 4.3.3.1, 4.3.3.3, 4.4.1.1}

When terrestrial ecosystems are substantially altered (in terms of plant cover, biomass, phenology, or plant group dominance), either through the effects of climate change or through other mechanisms such as conversion to agriculture or human settlement, the local, regional, and global climates are also affected (*high confidence*). The feedbacks between terrestrial ecosystems and climate include, among other mechanisms, changes in surface albedo, evapotranspiration, and greenhouse gas (GHG) emissions and uptake. The physical effects on the climate can be opposite in direction to the GHG effects, and can materially alter the net outcome of the ecosystem change on the global climate (*high confidence*). The regions where the climate is affected may extend beyond the location of the ecosystem that has changed. {4.2.4.1, 4.3.3.4}

Rising water temperatures, due to global warming, will lead to shifts in freshwater species distributions and worsen water quality problems, especially in those systems experiencing high anthropogenic loading of nutrients (*high confidence*). Climate change-induced changes in precipitation will substantially alter ecologically important attributes of flow regimes in many rivers and wetlands and exacerbate impacts from human water use in developed river basins (*medium confidence*). {4.3.3.3, Box CC-RF}

Many plant and animal species have moved their ranges, altered their abundance, and shifted their seasonal activities in response to observed climate change over recent decades (*high confidence*). They are doing so now in many regions and will continue to do so in response to projected future climate change (*high confidence*). The broad patterns of species and biome shifts toward the poles and higher in altitude in response to a warming climate are well established for periods thousands of years in the past (*very high confidence*). These general patterns of range shifts have also been observed over the last few decades in some well-studied species groups such as insects and birds and can be attributed to observed climatic changes (*high confidence*). Interactions between changing temperature, precipitation, and land use can sometimes result in range shifts that are downhill or away from the poles. Certainty regarding past species movements in response to changing climate, coupled with projections from a variety of models and studies, provides *high confidence* that such species movements will be the norm with continued warming. Under all RCP climate change scenarios for the second half of the 21st century, with *high confidence*: (1) community composition will change as a result of decreases in the abundances of some species and increases in others; and (2) the seasonal activity of many species will change differentially, disrupting life cycles and interactions between species. Composition and seasonal change will both alter ecosystem function. {4.2.1, 4.2.3, 4.3.2, 4.3.2.1, 4.3.2.5, 4.3.3, 4.4.1.1}

Many species will be unable to move fast enough during the 21st century to track suitable climates under mid- and high-range rates of climate change (i.e., RCP4.5, RCP6.0, and RCP8.5 scenarios) (*medium confidence*). The climate velocity (the rate of movement of the climate across the landscape) will exceed the maximum velocity at which many groups of organisms, in many situations, can disperse or migrate, except after mid-century in the RCP2.6 scenario. Populations of species that cannot keep up with their climate niche will find themselves in unfavorable climates, unable to reach areas of potentially suitable climate. Species occupying extensive flat landscapes are particularly vulnerable because they must disperse over longer distances than species in mountainous regions to keep pace with shifting climates. Species with low dispersal capacity will also be especially vulnerable: examples include many plants (especially trees), many amphibians, and some small mammals. For example, the maximum observed and modeled dispersal and establishment rates for mid- and late-successional tree species are insufficient to track climate change except in mountainous areas, even at moderate projected rates of climate change. Barriers to dispersal, such as habitat fragmentation, prior occupation of habitat by competing species, and human-made impediments such as dams on rivers and urbanized areas on land, reduce the ability of species to migrate to more suitable climates (*high confidence*). Intentional and accidental anthropogenic transport can speed dispersal. {4.3.2.5, 4.3.3.3}

Large magnitudes of climate change will reduce the populations, vigor, and viability of species with spatially restricted populations, such as those confined to small and isolated habitats, mountaintops, or mountain streams, even if the species has the biological capacity to move fast enough to track suitable climates (*high confidence*). The adverse effects on restricted populations are modest for low magnitudes of climate change (e.g., RCP2.6) but very severe for the highest magnitudes of projected climate change (e.g., RCP8.5). {4.3.2.5, 4.3.3.4, 4.3.4.1}

The capacity of many species to respond to climate change will be constrained by non-climate factors (*high confidence*), including but not limited to the simultaneous presence of inhospitable land uses, habitat fragmentation and loss, competition with alien species, exposure to new pests and pathogens, nitrogen loading, and tropospheric ozone. {4.2.4.6, 4.3.3.5, Figure 4-4}

The establishment, growth, spread, and survival of populations of invasive alien species have increased (*high confidence*), but the ability to attribute alien species invasion to climate change is low in most cases. Some invasive alien species have traits that favor their survival and reproduction under changing climates. Future movement of species into areas where they were not present historically will continue to be driven mainly by increased dispersal opportunities associated with human activities and by increased disturbances from natural and anthropogenic events, in some cases facilitated and promoted by climate change. {4.2.4.6, Figure 4-4}

4

A large fraction of terrestrial and freshwater species face increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other pressures, such as habitat modification, overexploitation, pollution, and invasive species (*high confidence*). The extinction risk is increased under all RCP scenarios, and the risk increases with both the magnitude and rate of climate change. While there is *medium confidence* that recent warming contributed to the extinction of some species of Central American amphibians, there is generally *very low confidence* that observed species extinctions can be attributed to recent climate change. Models project that the risk of species extinctions will increase in the future owing to climate change, but there is *low agreement* concerning the fraction of species at increased risk, the regional and taxonomic focus for such extinctions and the time frame over which extinctions could occur. Modeling studies and syntheses since the AR4 broadly confirm that a large proportion of species are projected to be at increased risk of extinction at all but the lowest levels of climate warming (RCP2.6). Some aspects leading to uncertainty in the quantitative projections of extinction risks were not taken into account in previous models; as more realistic details are included, it has been shown that the extinction risks may be either under- or overestimated when based on simpler models. {4.3.2.5}

Terrestrial and freshwater ecosystems have sequestered about a quarter of the carbon dioxide (CO_2) emitted to the atmosphere by human activities in the past 3 decades (*high confidence*). The net fluxes out of the atmosphere and into plant biomass and soils show large year-to-year variability; as a result there is *low confidence* in the ability to determine whether the net rate at which carbon has been taken up by terrestrial ecosystems at the global scale has changed between the decades 1991–2000 and 2001–2010. There is *high confidence* that the factors causing the current increase in land carbon include the positive effects of rising CO_2 on plant productivity, a warming climate, nitrogen deposition, and recovery from past disturbances, but *low confidence* regarding the relative contribution by each of these and other factors. {4.2.4.1, 4.2.4.2, 4.2.4.4, 4.3.2.2, 4.3.2.3, WGI AR5 6.3.1, 6.3.2.6}

The natural carbon sink provided by terrestrial ecosystems is partially offset at the decadal time scale by carbon released through the conversion of natural ecosystems (principally forests) to farm and grazing land and through ecosystem degradation (*high confidence*). Carbon stored in the terrestrial biosphere is vulnerable to loss back to the atmosphere as a result of the direct and indirect effects of climate change, deforestation, and degradation (*high confidence*). The net transfer of CO_2 from the atmosphere to the land is projected to weaken during the 21st century (*medium confidence*). The direct effects of climate change on stored terrestrial carbon include high temperatures, drought, and windstorms; indirect effects include increased risk of fires and pest and disease outbreaks. Experiments and modeling studies provide *medium confidence* that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water use efficiency, but at a diminishing rate; and *high confidence* that low availability of nutrients, particularly nitrogen, will limit the response of many natural ecosystems to rising CO_2. There is *medium confidence* that other factors associated with global change, including high temperatures, rising ozone concentrations, and in some places drought, decrease plant productivity by amounts comparable in magnitude to the enhancement by rising CO_2. There are few field-scale experiments on ecosystems at the highest CO_2 concentrations projected by RCP8.5 for late in the century, and none of these include the effects of other potential confounding factors. {4.2.4, 4.2.4.1, 4.2.4.2, 4.2.4.3, 4.2.4.4, 4.3.2.2, 4.3.3.1, Box 4-3, Box CC-VW, WGI AR5 6.4.3.3}

Increases in the frequency or intensity of ecosystem disturbances such as droughts, wind storms, fires, and pest outbreaks have been detected in many parts of the world and in some cases are attributed to climate change (*medium confidence*). Changes in the ecosystem disturbance regime beyond the range of natural variability will alter the structure, composition, and functioning of ecosystems (*high confidence*). Ecological theory and experimentation predict that ecological change resulting from altered disturbance regimes will be manifested as relatively abrupt and spatially patchy transitions in ecosystem structure, composition, and function, rather than gradual and spatially uniform shifts in location or abundance of species (*medium confidence*). {4.2.4.6, 4.3.3, 4.3.2.5, Box 4-3, Box 4-4, Figure 4-10}

4

Increased tree death has been observed in many places worldwide, and in some regions has been attributed to climate change (*high confidence*). In some places it is sufficiently intense and widespread as to result in forest dieback (*low confidence*). Forest dieback is a major environmental risk, with potentially large impacts on climate, biodiversity, wood production, water quality, amenity, and economic activity. In detailed regional studies in western and boreal North America, the tree mortality observed over the past few decades has been attributed to the effects of high temperatures and drought, or to changes in the distribution and abundance of insect pests and pathogens related, in part, to warming (*high confidence*). Tree mortality and associated forest dieback will become apparent in many regions sooner than previously anticipated (*medium confidence*). Earlier projections of increased tree growth and enhanced forest carbon sequestration due to increased growing season duration, rising CO_2 concentration, and atmospheric nitrogen deposition must be balanced by observations and projections of increasing tree mortality and forest loss due to fires and pest attacks. The consequences for the provision of timber and other wood products are projected to be highly variable between regions and products, depending on the balance of the positive versus negative effects of global change. {4.3.2, 4.3.3.1, 4.3.3.4, 4.3.3.5, 4.3.4, 4.3.4.2, Box 4-2, Box 4-3}

There is a high risk that the large magnitudes and high rates of climate change associated with low-mitigation climate scenarios (RCP4.5 and higher) will result within this century in abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, for example in the Amazon (*low confidence*) and Arctic (*medium confidence*), leading to substantial additional climate change. There are plausible mechanisms, supported by experimental evidence, observations, and model results, for the existence of ecosystem tipping points in both boreal-tundra Arctic systems and the rainforests of the Amazon basin. Continued climate change will transform the species composition, land cover, drainage, and permafrost extent of the boreal-tundra system, leading to decreased albedo and the release of GHGs (*medium confidence*). Adaptation measures will be unable to prevent substantial change in the boreal-Arctic system (*high confidence*). Climate change alone is not projected to lead to abrupt widespread loss of forest cover in the Amazon during this century a (*medium confidence*), but a projected increase in severe drought episodes, together with land use change and forest fire, would cause much of the Amazon forest to transform to less dense, drought- and fire-adapted ecosystems, and in doing so put a large stock of biodiversity at elevated risk, while decreasing net carbon uptake from the atmosphere (*low confidence*). Large reductions in deforestation, as well as wider application of effective wildfire management, lower the risk of abrupt change in the Amazon, as well as the impacts of that change (*medium confidence*). {4.2.4.1, 4.3.3.1.1, 4.3.3.1.3, 4.3.3.4, Figure 4-8, Box 4-3, Box 4-4}

Management actions can reduce, but not eliminate, the risk of impacts to terrestrial and freshwater ecosystems due to climate change, as well as increase the inherent capacity of ecosystems and their species to adapt to a changing climate (*high confidence*). The capacity for natural adaptation by ecosystems and their constituent organisms is substantial, but for many ecosystems and species it will be insufficient to cope with projected rates and magnitudes of climate change in the 21st century without substantial loss of species and ecosystem services, under medium-range warming (e.g., RCP6.0) or high-range warming scenarios (e.g., RCP8.5) (*medium confidence*). The capacity for ecosystems to adapt to climate change can be increased by reducing the other stresses operating on them; reducing the rate and magnitude of climate change; reducing habitat fragmentation and increasing connectivity; maintaining a large pool of genetic diversity and functional evolutionary processes; assisted translocation of slow moving organisms or those whose migration is impeded, along with the species on which they depend; and manipulation of disturbance regimes to keep them within the ranges necessary for species persistence and sustained ecosystem functioning. {4.4, 4.4.1, 4.4.2}

Adaptation responses to climate change in the urban and agricultural sectors can have unintended negative outcomes for terrestrial and freshwater ecosystems (*medium confidence*). For example, adaptation responses to counter increased variability of water supply, such as building more and larger impoundments and increased water extraction, will in many cases worsen the direct effects of climate change in freshwater ecosystems. {4.3.3.3, 4.3.4.6}

Widespread transformation of terrestrial ecosystems in order to mitigate climate change, such as carbon sequestration through planting fast-growing tree species into ecosystems where they did not previously occur, or the conversion of previously uncultivated or non-degraded land to bioenergy plantations, will lead to negative impacts on ecosystems and biodiversity (*high confidence*). For example, the land use scenario accompanying the mitigation scenario RCP2.6 features a large expansion of biofuel production, displacing natural forest cover. {4.2.4.1, 4.4.4}

4.1. Past Assessments

The topics assessed in this chapter were last assessed by the IPCC in 2007, principally in WGII AR4 Chapters 3 (Kundzewicz et al., 2007) and 4 (Fischlin et al., 2007), but also in WGII AR4 Sections 1.3.4 and 1.3.5 (Rosenzweig et al., 2007). The WGII AR4 SPM stated "Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases," though they noted that documentation of observed changes in tropical regions and the Southern Hemisphere was sparse (Rosenzweig et al., 2007). Fischlin et al. (2007) found that 20 to 30% of the plant and animal species that had been assessed to that time were considered to be at increased risk of extinction if the global average temperature increase exceeds 2°C to 3°C above the preindustrial level with *medium confidence*, and that substantial changes in structure and functioning of terrestrial, marine, and other aquatic ecosystems are *very likely* under that degree of warming and associated atmospheric CO_2 concentration. No time scale was associated with these findings. The carbon stocks in terrestrial ecosystems were considered to be at high risk from climate change and land use change. The report warned that the capacity of ecosystems to adapt naturally to the combined effect of climate change and other stressors is likely to be exceeded if greenhouse gas (GHG) emission continued at or above the then-current rate.

4.2. A Dynamic and Inclusive View of Ecosystems

There are three aspects of the contemporary scientific view of ecosystems that are important to know for policy purposes. First, ecosystems usually have imprecise and variable boundaries. They span a wide range of spatial scales, nested within one another, from the whole biosphere, down through its major ecosystem types (biomes), to local and possibly short-lived associations of organisms. Second, the human influence on ecosystems is globally pervasive. Humans are regarded as an integral, rather than separate, part of social-ecological systems (Gunderson and Holling, 2001; Berkes et al., 2003). Ecosystems are connected across boundaries through the movement of energy, materials, and organisms, and subsidies between terrestrial and freshwater systems are known to be particularly important (Polis et al., 1997; Loreau et al., 2003). As a consequence, human activities in terrestrial systems can significantly impact freshwater ecosystems and their biota (Allan, 2004). The dynamics of socio-ecological systems are governed not only by biophysical processes such as energy flows, material cycles, competition, and predation, but also by social processes such as economics, politics, culture, and individual preferences (Walker and Salt, 2006). Third, ecologists do not view ecosystems as necessarily inherently static and at equilibrium in the absence of a human disturbance (Hastings, 2004). Ecosystems vary over time and space in the relative magnitude of their components and fluxes, even under a constant environment, owing to internal dynamics (Scheffer, 2009). Furthermore, attempts to restrict this intrinsic variation—or that resulting from externally generated disturbances—are frequently futile, and may damage the capacity of the ecosystem to adapt to a changing environment (Folke et al., 2004). This contrasts with the popular view that ecosystems exhibit a "balance of Nature" and benefit from being completely protected from disturbance.

4.2.1. Ecosystems, Adaptation, Thresholds, and Tipping Points

The term "adaptation" has different meanings in climate policy, ecology, and evolutionary biology. In climate policy (see Glossary) it implies human actions intended to reduce negative outcomes. In ecology, ecosystems are said to be adaptive because their composition or function can change in response to a changing environment, without necessarily involving deliberate human actions (see Section 4.4.1). In evolutionary biology, adaptation means a change in the genetic properties of a population of individuals as a result of natural selection (Section 4.4.1.2), a possibility seen since the Fourth Assessment Report as increasingly relevant to climate change.

The notion of thresholds has become a prominent ecological and political concern (Knapp, A.K. et al., 2008; Lenton et al., 2008; Leadley et al., 2010). To avoid policy confusion, three types of threshold need to be distinguished. The first reflects a human preference that the ecosystem stays within certain bounds, such as above a certain forest cover. These can be, by definition, negotiated. The second type reflects fundamental biological or physical properties, for instance the temperature at which frozen soils thaw (see Box 4-4) or the physiological tolerance limits of species. The third type is caused by system dynamics: the point at which the net effect of all the positive and negative feedback loops regulating the system is sufficiently large and positive that a small transgression becomes sufficiently amplified to lead to a change in ecosystem state called a regime shift (Lenton et al., 2008). The new state exhibits different dynamics, mean composition, sensitivity to environmental drivers, and flows of ecosystem services relative to the prior state. This type of threshold is called a "tipping point" (defined in the Glossary as a level of change in system properties beyond which a system reorganizes, often abruptly, and persists in its new state even if the drivers of the change are abated) and is important in the context of climate change because its onset may be abrupt, hard to predict precisely, and effectively irreversible (Scheffer et al., 2009; Leadley et al., 2010; Barnosky et al., 2012; Brook et al., 2013; Hughes et al., 2013). Many examples of tipping points have now been identified (Scheffer, 2009). Regional-scale ecosystem tipping points have not occurred in the recent past, but there is good evidence for tipping points in the distant past (Section 4.2.3) and there is concern that they could occur in the near future (see Boxes 4-3 and 4-4).

The early detection and prediction of ecosystem thresholds, particularly tipping points, is an area of active research. There are indications (Scheffer, 2009) that an increase in ecosystem variability signals the impending approach of a threshold. In practice, such signals may not be detectable against background noise and uncertainty until the threshold is crossed (Biggs et al., 2009). The dynamics of ecosystems are complex and our present level of knowledge is inadequate to predict all ecosystem outcomes with confidence, even if the future climate were precisely known.

Field observations over the past century in numerous locations in boreal, temperate, and tropical ecosystems have detected biome shifts, the replacement at a location of one suite of species by another (*high confidence*). The effect is usually of biomes moving upward in elevation and to higher latitudes (Gonzalez et al., 2010; see Figure 4-1). These shifts

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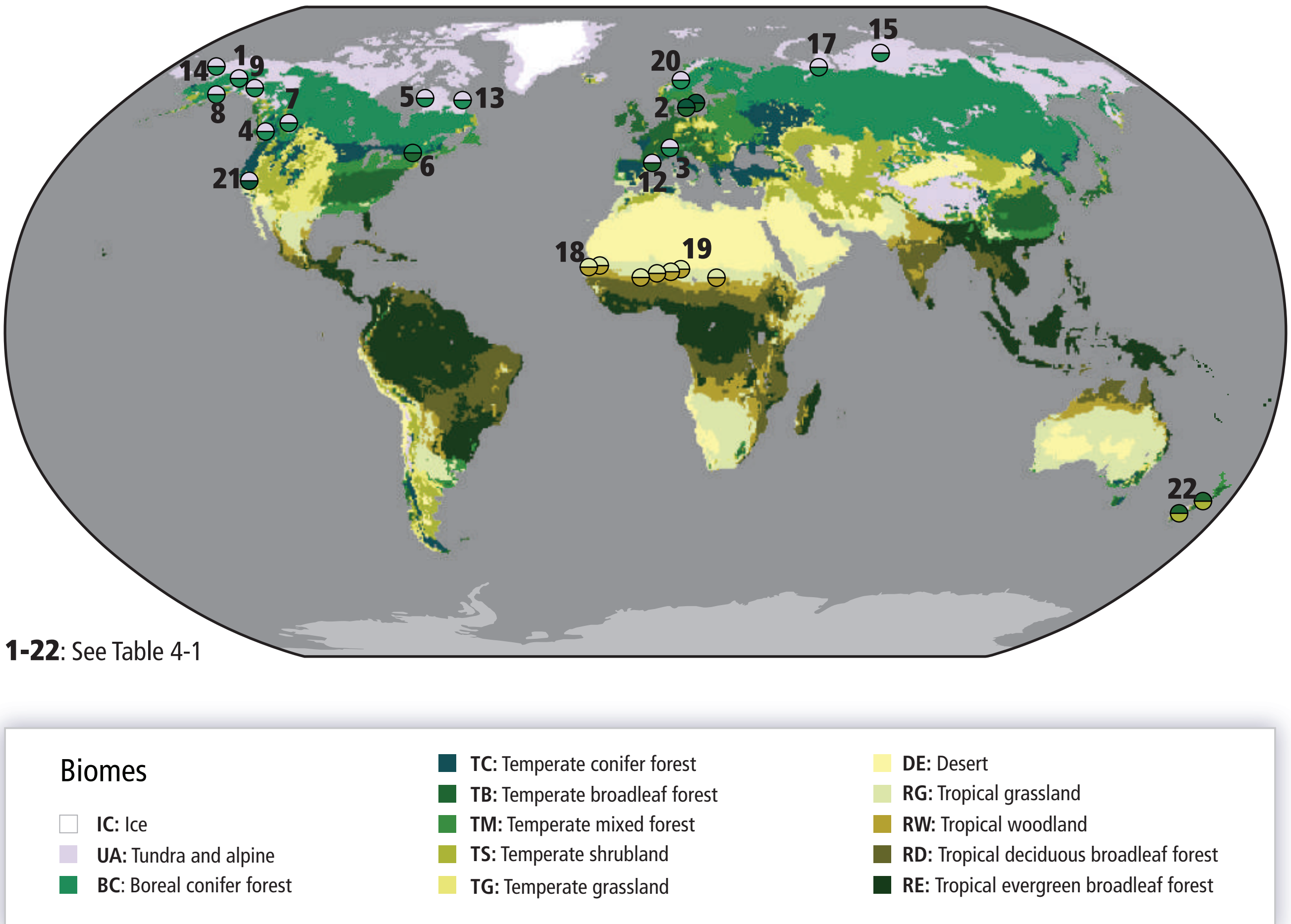

Figure 4-1 | Locations of observed biome shifts during the 20th century, listed in Table 4-1, derived from Gonzalez et al. (2010). The color of each semicircle indicates the retracting biome (top for North America, Europe, Asia; bottom for Africa and New Zealand) and the expanding biome (bottom for North America, Europe, Asia; top for Africa and New Zealand), according to published field observations. Biomes, from poles to equator: ice (IC), tundra and alpine (UA), boreal conifer forest (BC), temperate conifer forest (TC), temperate broadleaf forest (TB), temperate mixed forest (TM), temperate shrubland (TS), temperate grassland (TG), desert (DE), tropical grassland (RG), tropical woodland (RW), tropical deciduous broadleaf forest (RD), tropical evergreen broadleaf forest (RE). The background is the potential biome according to the MC1 dynamic global vegetation model under the 1961–1990 climate. No shift was observed on locations 10, 11, 16, and 23 (see Table 4-1).

have often been attributed to anthropogenic climate change, as biome distribution is known to broadly reflect climate zones, and the shifts have been observed in areas without major human disturbance (*medium confidence*; see Table 4-1). Projections of future vegetation distribution under climate change indicate that many biomes could shift substantially, including in areas where ecosystems are largely undisturbed by direct human land use (Figure 4-2). The extent of the shift increases with increasing global mean warming, without a sudden threshold (Scholze et al., 2006; Pereira et al., 2010; Rehfeldt et al., 2012).

4.2.2. Methods and Models Used

Analysis of the current and past impacts of climate change on terrestrial and freshwater ecosystems and their projection into the future relies on three general approaches: inference from analogous situations in the past or elsewhere in the present; manipulative experimentation, deliberately altering one of a few factors at a time; and models with a mechanistic or statistical basis. Studies of the relatively distant past are discussed in depth in Section 4.2.3. Inferences from present spatial patterns in relation to climate is at the core of climate envelope niche modeling, a well-established but limited statistical technique for making projections of the future distribution under equilibrium conditions (Elith and Leathwick, 2009). Representing the rate of change during the non-equilibrium conditions that will prevail over the next century requires a more mechanistic approach, of which there are some examples (e.g., Keith et al., 2008; Kearney and Porter, 2009). Changes in ecosystem function are usually determined by experimentation (see examples in Section 4.3.3) and are modeled using mechanistic models, in many cases with relatively high uncertainty (Seppelt et al., 2011).

4.2.3. Paleoecological Evidence

Paleoclimatic observations and modeling indicate that the Earth's climate has always changed on a wide range of time scales. In many cases, particularly over the last million years, it has changed in ways that are well understood in terms of both patterns and causes (Jansen et al., 2007; see WGI AR5 Chapter 5). Paleoecological records demonstrate with *high confidence* that the planet's biota (both terrestrial and aquatic),

Table 4-1 | Biome shifts of the 20th century from published field research that examined trends over periods >30 years for biomes in areas where climate (rather than land use change or other factors) predominantly influenced vegetation, derived from a systematic analysis of published studies (Gonzalez et al., 2010). Pre-AR4 publications are included to provide a comprehensive review. Shift type: elevational (E), latitudinal (L), examined but not detected (N). The biome abbreviations match those in Figure 4-1. Rate of change in temperature (Temp.) and fractional rate of change in precipitation (Precip.) are derived from linear least squares regression of 1901–2002 data (Mitchell and Jones, 2005; Gonzalez et al., 2010). The table provides general regional climate trends at 50 km spatial resolution because the references do not give uniform site-specific climate data to compare across locations. The regional trends are consistent with local trends reported in each reference. *Rate significant at P ≤ 0.05.

Location	Reference	Plots	Time period	Shift type	Retracting biome	Expanding biome	Temp. change (°C century^{-1})	Precip. change (% century^{-1})
1. Alaska Range, Alaska, USA	Lloyd and Fastie (2003)	18	1800–2000	L	UA	BC	1.1*	3
2. Baltic Coast, Sweden	Walther et al. (2005)	7	1944–2003	L	TC	TB	0.6*	8
3. Becca di Viou, Italy	Leonelli et al. (2011)	1	1700–2008	E	UA	BC	0.9*	–6
4. Garibaldi, British Columbia, Canada	Brink (1959)	1	1860–1959	E	UA	BC	0.7*	16*
5. Goulet Sector, Québec, Canada	Payette and Filion (1985)	2	1880–1980	E	UA	BC	1.4*	19*
6. Green Mountains, Vermont, USA	Beckage et al. (2008)	33	1962–2005	E	BC	TB	1.6*	6
7. Jasper, Alberta, Canada	Luckman and Kavanagh (2000)	1	1700–1994	E	UA	BC	0.6	21*
8. Kenai Mountains, Alaska, USA	Dial et al. (2007)	3	1951–1996	E	UA	BC	0.7	6
9. Kluane Range, Yukon, Canada	Danby and Hik (2007)	2	1800–2000	E	UA	BC	0.7	5
10. Low Peninsula, Québec, Canada	Payette and Filion (1985)	1	1750–1980	N	—	—	1.4*	19*
11. Mackenzie Mountains, Northwest Territories, Canada	Szeicz and Macdonald (1995)	13	1700–1990	N	—	—	1.4*	3
12. Montseny Mountains, Catalonia, Spain	Peñuelas and Boada (2003)	50	1945–2001	E	UA	TB	1.2*	–3
13. Napaktok Bay, Labrador, Canada	Payette (2007)	2	1750–2000	L	UA	BC	1.1*	5
14. Noatak, Alaska, USA	Suarez et al. (1999)	18	1700–1990	L	UA	BC	0.6	19*
15. Putorana Mountains, Russian Federation	Kirdyanov et al. (2012)	10	1500–2000	E	UA	BC	0.3	10
16. Rahu Saddle, New Zealand	Cullen et al. (2001)	7	1700–2000	N	—	—	0.6*	3
17. Rai-Iz, Urals, Russian Federation	Devi et al. (2008)	144	1700–2002	E	UA	BC	0.3	35*
18. Sahel, Sudan, Guinea zones; Senegal	Gonzalez (2001)	135	1945–1993	L	RW	RG	0.4*	–48*
19. Sahel, Burkina Faso, Chad, Mali, Mauritania, Niger	Gonzalez et al. (2012)	14	1960–2000	L	RW	RG	–0.01* to 0.8*	–31* to 9
20. Scandes, Sweden	Kullman and Öberg (2009)	123	1915–2007	E	UA	BC	0.8*	25*
21. Sierra Nevada, California, USA	Millar et al. (2004)	10	1880–2002	E	UA	TC	–0.1	21*
22. South Island, New Zealand	Wardle and Coleman (1992)	22	1980–1990	E	TS	TB	0.6*	3
23. Yambarran, Northern Territory, Australia	Sharp and Bowman (2004)	33	1948–2000	N	—	—	–0.06	35*

carbon cycle, and associated feedbacks and services have responded to this climatic change, particularly when the climatic change was as large as that projected during the 21st century under mid- to high-end radiative forcing pathways (e.g., MacDonald et al., 2008; Claussen, 2009; Arneth et al., 2010; Dawson et al., 2011; Willis and MacDonald, 2011). Excellent examples of past large climate change events that drove large ecological change, as well as recovery periods in excess of a million years, include the events that led to the Earth's five mass extinctions in the distant past (i.e., during the Ordovician, about 443 Ma, the Devonian, about 359 Ma, the Permian, about 251 Ma, the Triassic, about 200 Ma, and the Cretaceous, about 65 Ma; Barnosky et al., 2011). Major ecological change was also driven by climate change during the Paleocene-Eocene Thermal Maximum (PETM, 56 Ma; Wing et al., 2005; Jaramillo et al., 2010; Wing and Currano, 2013), the early Eocene Climatic Optimum (EECO, 53 to 50 Ma; Woodburne et al., 2009), the Pliocene (5.3 to 2.6 Ma; Haywood and Valdes, 2006; Haywood et al., 2011), and the Last Glacial Maximum (LGM) to Holocene transition between 21 and 6 ka (MacDonald et al., 2008; Clark et al., 2009; Gill et al., 2009; Williams, J.W. et al., 2010; Prentice et al., 2011; Daniau et al., 2012). The paleoecological record thus provides *high confidence* that large global climate change, comparable in magnitude to that projected for the 21st century, can result in large ecological changes, including large-scale biome shifts, reshuffling of communities, and species extinctions.

Rapid, regional warming before and after the Younger Dryas cooling event (11.7 to 12.9 ka) provides a relatively recent analogy for climate change at a rate approaching, for many regions, that projected for the 21st century for all Representative Concentration Pathways (RCPs; Alley et al., 2003; Steffensen et al., 2008). Ecosystems and species responded rapidly during the Younger Dryas by shifting distributions and abundances, and there were some notable large animal extinctions, probably exacerbated by human activities (Gill et al., 2009; Dawson et al., 2011). In some regions, species became locally or regionally extinct (extirpated), but there is no evidence for climate-driven global-scale extinctions during this period (Botkin et al., 2007; Willis, K.J. et al., 2010). However, the Younger Dryas climate changes differ from those projected for the future because they were regional rather than global; may have only regionally exceeded rates of warming projected for the future; and started from a baseline substantially colder than present (Alley et al., 2003). The mid-Holocene, about 6 ka, provides a very recent example of the effects of modest climate change. Regional mean warming during this period (mean annual temperature about 0.5°C to 1.0°C above

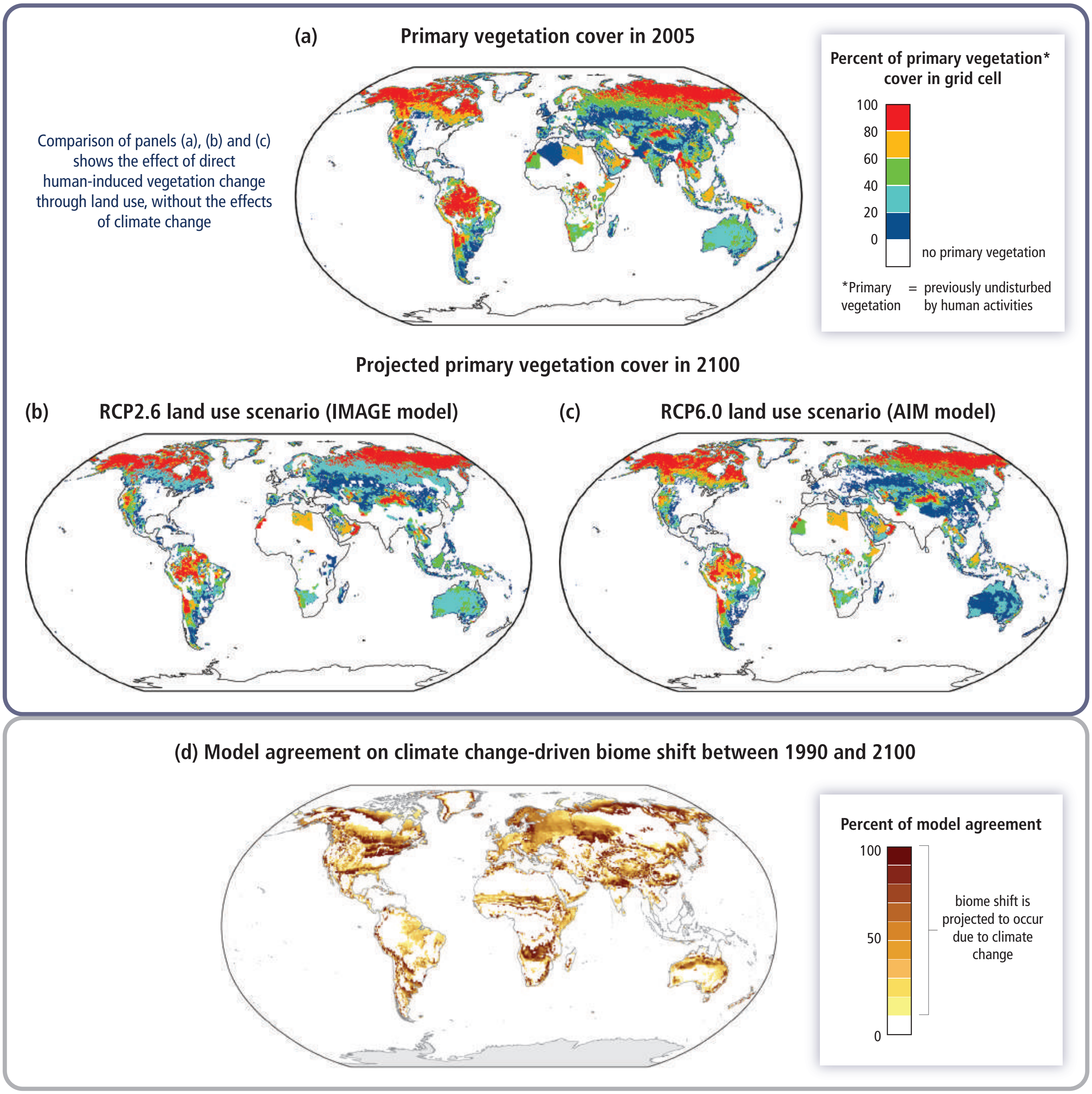

Figure 4-2 | Projections of climate change-driven biome shifts in the context of direct human land use. (a) Fraction of land covered by primary vegetation in 2005 (Hurtt et al., 2011); (b) Fraction of land covered by primary vegetation in 2100 under the RCP2.6 land use scenario, with no effect of climate change (Hurtt et al., 2011); (c) Fraction of land covered by primary vegetation in 2100 under the RCP6.0 land use scenario, with no effect of climate change (Hurtt et al., 2011). (d) Fraction of simulations showing climate change-driven biome shift for any level of global warming between 1990 and 2100, with no direct anthropogenic land use change, using the MC1 vegetation model under 9 CMIP3 climate projections (3 GCMs, each forced by the SRES A2, A1B, and B1 scenarios; Gonzalez et al., 2010); Comparison of colored areas in (d) with those in (a) shows where climate-driven biome shifts would occur in current areas of primary vegetation. Comparison of (b) and (c) with (a) illustrates two scenarios of how primary vegetation could change due to direct human land use, irrespective of the effects of climate change. (b) shows the land use scenario associated with RCP2.6, in which global climate change is projected to be smaller than that driving the biome shifts in (d) as a result of mitigation measures, some of which involved land use. (c) shows the land use scenario associated with RCP6.0, in which global climate change is projected to be larger than RCP2.6 so biome shifts similar to those in (d) may occur alongside the projected land use changes in (c). For example, climate change-driven biome shift is projected in many Arctic land areas (d) which are unaffected by direct human land use at the present day (a) and in the RCP2.6 and 6.0 land use scenarios (b, c), indicating that climate change is the dominant influence on Arctic land ecosystems in these scenarios. In contrast, in Borneo, none of the GCMs analysed by Gonzalez et al. (2010) project climate change-driven biome shift (d), and instead a reduction in primary vegetation cover occurs in the mitigation scenario RCP2.6 as a consequence of direct human land use (b). A smaller reduction occurs in RCP6.0. Land use is therefore projected to be the dominant driver of change in Borneo in these scenarios. In the boreal forest regions of North America, Europe, and north-west Asia, climate change-driven biome shift (d) is projected in regions already subject to some influence of present-day human land use (a), and increased land use leading to further reductions in primary vegetation occur in both RCP2.6 (b) and RCP6.0 (c). Hence in these boreal forest regions, both climate change and land use are projected to be drivers of ecosystem change in these scenarios. Further details of the RCP land use/cover scenarios are given in Box 4-1, Figure 4-3, and Table 4-2.

preindustrial in some continental-scale regions; see WGI AR5 Section 5.5.1) was the same order of magnitude as the warming the Earth has experienced over the 20th century. Ecological effects were small compared to periods with larger climate excursions, but even this small warming was characterized by frequent fires in drier parts of the Amazon (Mayle and Power, 2008), development of lush vegetation and lakes in a wetter Sahara (Watrin et al., 2009), temperate deciduous forests in Europe expanding further north and up to higher elevations (Prentice et al., 1996), and large-scale migration of Boreal Forest into a warmer tundra (Jackson and Overpeck, 2000). Past climate change, even more modest than mid-range projected future change, also clearly impacted inland water systems (e.g., Smol and Douglas, 2007a; Battarbee et al., 2009; Beilman et al., 2009). However, there are no exact analogs for future climate change: none of the well-studied past periods of large climate change involved simultaneously the rates, magnitude, and spatial scale of climate and atmospheric carbon dioxide (CO_2) change projected for the 21st century and beyond (Jansen et al., 2007; Schulte et al., 2010; Wing and Currano, 2013; see WGI AR5 Chapter 5). Direct analogy with the paleoecological record is also unwarranted because future climate change will interact with other global changes such as land use change, invasive species, pollution, and overexploitation of natural resources (Pereira et al., 2010). There is *high confidence* that these interactions will be important: the paleoecological record provides *medium confidence* (*medium evidence*, *high agreement*) that exploitation by humans helped drive many large mammal species to extinction during periods of climate change in the past (Lorenzen et al., 2011).

It has been demonstrated that state-of-the-art vegetation models are able to simulate much of the biome-level equilibrium response of terrestrial vegetation to large paleoclimate change (Prentice et al., 1996, 2011; Salzmann et al., 2008). The same types of models predict large changes in species ranges, ecosystem function, and carbon storage when forced by 21st century climate change, although the future situation is complicated by land use and other factors absent in the paleoenvironmental case (Sitch et al., 2008; Cheaib et al., 2012; see WGI AR5 Section 6.4). Thus, the paleoecological record and models that have been tested against it provide a coherent message that biomes will alter their functioning and composition in response to changing and often novel future climates: they will move as species mixtures change (Section 4.3.2.5 has more specific information on projected migration rates), novel plant communities will emerge, and significant carbon stock changes will take place (Williams and Jackson, 2007; MacDonald, 2010; Prentice et al., 2011; Willis and MacDonald, 2011). The paleoecological record and models provide *high confidence* that it will be difficult or impossible to maintain many ecological systems in their current states if global warming exceeds 2°C to 3°C, raising questions about the long-term viability of some current protected areas and conservation schemes, particularly where the objective is to maintain present-day species mixtures (Jackson and Hobbs, 2009; Hickler et al., 2012).

Much of the complex, time-dependent change at regional scales has not yet been simulated by models. The paleoecological record indicates that vegetation in many parts of the world has the potential to respond within years to a few decades to climate change (e.g., Mueller, A.D. et al., 2009; Watrin et al., 2009; Williams et al., 2009; Harrison and Goni, 2010). This record provides a critical opportunity for model evaluation that should be more thoroughly exploited to gain confidence in time-dependent simulations of future change, particularly given the complex role that interacting climate change and vegetation disturbance has played in the past (e.g., Jackson et al., 2009; Marlon et al., 2009; Williams et al., 2009; Daniau et al., 2010; Dawson et al., 2011). The paleoecological record also highlights the importance of including the direct effects of changing atmospheric CO_2 levels in efforts to simulate future ecosystem functioning and plant species competition (Prentice et al., 2011; Woillez et al., 2011; Bond and Midgley, 2012; Claussen et al., 2013).

The paleoclimatic record also reveals that past radiative climate forcing change was slower than that anticipated for the 21st century (see WGI AR5 Chapters 5, 8, and 12), but even these slower changes often drove surprisingly abrupt, nonlinear, regional-scale change in terrestrial and inland water systems (e.g., Harrison and Goni, 2010; Williams et al., 2011), as did even slower climate change during the most recent Holocene interglacial (e.g., Booth et al., 2005; Kropelin et al., 2008; Williams, J.W. et al., 2010; Williams et al., 2011). In all cases, specific periods of abrupt ecological response were regionally distinct in nature and were less synchronous for small, slow changes in forcing (e.g., during the Holocene) than for the global-scale rapid changes listed at the start of this section. State-of-the-art climate and Earth System Models (ESMs) are unable to simulate the full range of abrupt change observed in many of these periods (e.g., Valdes, 2011). Thus there is *high confidence* that these models may not capture some aspects of future abrupt climate change and associated ecosystem impacts (Leadley et al., 2010).

Frequently Asked Questions

FAQ 4.1 | How do land use and land cover changes cause changes in climate?

Land use change affects the local as well as the global climate. Different forms of land cover and land use can cause warming or cooling and changes in rainfall, depending on where they occur in the world, what the preceding land cover was, and how the land is now managed. Vegetation cover, species composition, and land management practices (such as harvesting, burning, fertilizing, grazing, or cultivation) influence the emission or absorption of greenhouse gases. The brightness of the land cover affects the fraction of solar radiation that is reflected back into the sky, instead of being absorbed, thus warming the air immediately above the surface. Vegetation and land use patterns also influence water use and evapotranspiration, which alter local climate conditions. Effective land use strategies can also help to mitigate climate change.

4.2.4. Multiple Stressors Interacting with Climate Change

The climatic and non-climatic drivers of ecosystem change need to be distinguished if the joint and separate attribution of changes to their causes is to be performed (see Chapter 18). In this section we elaborate on factors affecting ecosystems, operating simultaneously with climate change. These factors share underlining drivers with one another and with climate change to varying degrees; together they form a syndrome known as "global change." The individual effects of climate change, habitat loss and fragmentation, chemical pollution, overharvesting, and invasive alien species are increasingly well documented (Millennium Ecosystem Assessment, 2005c; Settele et al., 2010a) but much less is known about their combined consequences. Ecosystem changes may occur in cascades, where a change in one factor precipitates increased vulnerability with respect to other factors (Wookey et al., 2009) or propagates through the ecosystem as a result of species interactions (Gilman et al., 2010). Multiple stressors can act in a non-additive way (Shaw et al., 2002; Settele et al., 2010b; Larsen et al., 2011), potentially invalidating findings and interventions based on single-factor analysis. For instance, Larsen et al. (2011) demonstrated that non-additive interactions among the climate factors in a multifactor experiment were frequent and most often antagonistic, leading to smaller effects than predicted from the sum of single factor effects. Leuzinger et al. (2011) and Dieleman et al. (2012) have synthesized multifactor experiments and demonstrated that, in general, the effect size is reduced when more factors are involved, but Leuzinger et al. (2011) suggest that multifactor models tend to show the opposite tendency.

4.2.4.1. Land Use and Cover Change

Land use and cover change (LUCC) is both a cause (WGI AR5 Section 6.1.2) and a consequence of climate change. It is the major driver of current ecosystem and biodiversity change (Millennium Ecosystem Assessment, 2005b) and a key cause of changes in freshwater systems (Section 4.3.3.3). In tropical and subtropical areas of Asia, Africa, Oceania, and South America, the dominant contemporary changes are conversion of forests and woodlands to annual and perennial agriculture, grazing pastures, industrial logging, and commercial plantations, followed by conversion of savannas, grasslands, and pastures to annual agriculture (Hosonuma et al., 2012; Macedo et al., 2012). In Europe there is net conversion of agricultural lands to forest (Rounsevell and Reay, 2009; Miyake et al., 2012). Conversion of peatlands to agriculture has been an important source of carbon to the atmosphere in Southeast Asia (Limpens et al., 2008; Hooijer et al., 2010; see Section 4.3.3.3).

Contemporary drivers of LUCC include rising demand for food, fiber, and bioenergy and changes in lifestyle and technologies (Hosonuma et al., 2012; Macedo et al., 2012). By mid-century climate change is projected to become a major driver of land cover change (Leadley et al., 2010). Non-climate environmental changes such as nitrogen deposition, air pollution, and altered disturbance regimes are also implicated in LUCC. Some of the underlying drivers of LUCC are also direct or indirect drivers of climate change (Cui and Graf, 2009; McAlpine et al., 2009; Mishra et al., 2010; Schwaiger and Bird, 2010; van der Molen et al., 2011; Groisman et al., 2012); this cause-and-effect entanglement of climate change and LUCC can confound the detection of climate change and make attribution to one or the other difficult. Local-to-regional climate change was at least partly attributed to LUCC in 11 of 26 studies reviewed for this chapter, generally with *limited evidence* and *low confidence*. (Direct climate effects attributed to LUCC: Cui and Graf, 2009; Li et al., 2009; McAlpine et al., 2009; Zhang et al., 2009; Fall et al., 2010; Jin et al., 2010; Mishra et al., 2010; Schwaiger and Bird, 2010; Wu et al., 2010; Carmo et al., 2012; Groisman et al., 2012. No climate effects studied: Suarez et al., 1999; Saurral et al., 2008; Tseng and Chen, 2008; Wang et al., 2008; Cochrane and Barber, 2009; Jia, B. et al., 2009; Rounsevell and Reay, 2009; Graiprab et al., 2010; Martin et al., 2010; Wiley et al., 2010; Clavero et al., 2011; Dai et al., 2011; Gao and Liu, 2011; Viglizzo et al., 2011; Yoshikawa and Sanga-Ngoie, 2011).

LUCC (and land use itself) contributes to changes in the climate through altering the GHG concentrations in the atmosphere, surface and cloud albedos, surface energy balance, wind profiles, and evapotranspiration, among other mechanisms. The phrase "biophysical effects" is shorthand for the effect vegetation has on the climate other than through its role as a source or sink of GHGs. These effects are now well documented, significant, and are increasingly included in models of global and regional climate change. The GHG and biophysical effects of vegetation can be opposite in sign (de Noblet-Ducoudre et al., 2012) and operate at different scales. For instance, conversion of forest to non-forest generally releases CO_2 from biomass and soils to the atmosphere (causing warming globally), but may result in an increase in seasonally averaged albedo (local and global cooling, Davin et al., 2007) and a decrease in transpiration (local, but not global warming). Findell et al. (2007) concluded on the basis of model studies that the non-GHG climate impacts of LUCC were generally minor, but nevertheless significant in some regions. Brovkin et al. (2013), projecting the overall effect of LUCC on climate change for the 21st century, found LUCC to be a small driver globally, but locally important. Most global climate models suggest local average cooling effects following forest conversion to croplands and pastures (Pitman et al., 2009; Longobardi et al., 2012). Satellite observations suggest that the effect of conversion of the Brazilian savannas (*cerrado*) to pasture was to induce a local warming that was partly reversed when the pasture was subsequently converted to sugarcane (Loarie et al., 2011). Several modeling studies suggest that the global surface air temperature response to deforestation depends on the latitude at which deforestation occurs. High-latitude deforestation results in global cooling, low-latitude deforestation causes global warming, and the mid-latitude response is mixed (Bathiany et al., 2010; Davin and de Noblet-Ducoudre, 2010; van der Molen et al., 2011; Longobardi et al., 2012), with some exceptions documented for boreal forests (Spracklen et al., 2008). Boreal and tropical forests influence the climate for different reasons: boreal forests have low albedo (i.e., reflect less solar radiation, especially in relation to a snowy background; Levis, 2010; Mishra et al., 2010; Longobardi et al., 2012) and tropical forests pump more water and aerosols into the atmosphere than non-forest systems in similar climates (Davin and de Noblet-Ducoudre, 2010; Delire et al., 2011; Pielke et al., 2011). The implications of these findings for afforestation as a climate mitigation action are discussed in Section 4.3.4.5. Forests may also influence regional precipitation through biophysical effects (Butt et al., 2011; Pielke et al., 2011; see Section 4.3.3).

In summary, changes in land cover have biophysical effects on the climate, sometimes opposite in direction to GHG-mediated effects,

Box 4-1 | Future Land Use Changes

Assessment of climate change effects on terrestrial and inland freshwater ecosystems requires the simultaneous consideration of land use and cover change (LUCC). The world is undergoing important shifts in land use, driven by accelerating demand for food, feed, fiber, and fuel. The main underlying driver is the rate at which per capita consumption is growing, particularly in emerging economies (Tilman et al., 2011). Policy shifts in developed countries favoring biofuel production have also contributed (Searchinger et al., 2008; Lapola et al., 2010; Miyake et al., 2012). Agricultural commodity prices have risen and may stay high through 2020 (OECD and FAO, 2010), owing to (1) demand growth outpacing supply growth, exacerbated by climate-related crop failure (Lobell et al., 2011); (2) decline in the rate of improvement in agricultural productivity (Ray et al., 2012); (3) shortage of arable land not already under cultivation, especially in the temperate zone; (4) growing pressure on as-yet uncultivated ecosystems on soils that are potentially suitable for cultivation and that are concentrated in tropical latitudes, especially South America and Africa (Lambin and Meyfroidt, 2011); and (5) declining area under cultivation in temperate zones, mainly in developed countries. The shortage of arable land in temperate systems could put pressure on marginal or sensitive landscapes, mainly in Latin America's *cerrados* and grasslands (Brazil, Argentina) and in African savannas (Sudan, Democratic Republic of Congo, Mozambique, Tanzania, Madagascar) (Lambin and Meyfroidt, 2011).

Deforestation in developing countries correlates with the export of agricultural commodities (DeFries et al., 2010). Future LUCC remains uncertain, as it depends on economic trends and policies themselves dependent on complex political and social processes, including climate policy. By 2012, the deforestation rate in the Brazilian Amazon had declined by 77% below its 1996–2005 average (Nepstad et al., 2009; INPE, 2013) as a result of policy and market signals (Soares-Filho et al., 2010). This single trend represents a 1.5% reduction in global anthropogenic carbon emissions (Nepstad et al., 2013).

Table 4-2 | Summary of drivers and outcomes of Land Use and Land Cover Change (LUCC) scenarios associated with Representative Concentration Pathways (RCPs; Hurtt et al., 2011). RCPs are identified with the radiative forcing by 2100 (8.5, 6.0, 4.5, and 2.6 W m^{-2}) and by the name of the model used to generate the associated land use/cover scenarios (MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact), AIM (Asia-Pacific Integrated Model), GCAM (Global Change Assessment Model), and IMAGE (Integrated Model to Assess the Global Environment); see Hurtt et al. (2011) for further details).

RCP	Model and references	Key assumptions/drivers	Land use/cover outcomes
8.5	MESSAGE; Riahi et al. (2007)	• No climate change mitigation actions; radiative forcing still rising at 2100. • Strong increase in agricultural resource use driven by the increasing population (rises to 12 billion people by 2100). • Yield improvements and intensification assumed to account for most of production increases.	• Increase in cultivated land by about 305 million ha from 2000 to 2100. • Forest cover declines by 450 million ha from 2000 to 2100. • Arable land use in developed countries slightly decreased — all of the net increases occur in developing countries.
6.0	AIM; Fujino et al. (2006), Hijioka et al. (2008)	• Mitigation actions taken late in the century to stabilize radiative forcing at 6 W m^{-2} after 2100. • Population growth and economic growth. • Increasing food demand drives cropland expansion .	• Urban land use increases. • Cropland area expands. • Grassland area declines. • Total forested area extent remains constant.
4.5	GCAM; Smith and Wigley (2006), Wise et al. (2009)	• Mitigation stabilizes radiative forcing at 4.5 W m^{-2} before 2100. • Assumes that global greenhouse gas emissions prices are invoked to limit emissions and therefore radiative forcing. Emissions pricing assumes all carbon emissions are charged an equal penalty price, so reductions in land use change carbon emissions available as mitigation. • Food demand is met through crop yield improvements, dietary shifts, production efficiency, and international trade.	• Preservation of large stocks of terrestrial carbon in forests. • Overall expansion in forested area. • Agricultural land declines slightly due to afforestation.
2.6	IMAGE; van Vuuren et al. (2006), van Vuuren et al. (2007)	• Overall trends in land use and land cover are determined mainly by demand, trade, and production of agricultural products and bioenergy. • Expansion of croplands largely due to bioenergy production. • Production of animal products is met through shift from extensive to more intensive animal husbandry.	• Much agriculture relocates from high-income to low-income regions. • Increase in bioenergy production, new area for bioenergy crops near current agricultural areas. • Pasture largely constant.

Continued next page →

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Box 4-1 (continued)

Each of the four main Representative Concentration Pathways (RCPs) used for future climate projections has a spatially explicit future land use scenario consistent with both the emissions scenario and the underlying associated socioeconomic scenario simulated by integrated assessment models, as well as conditions in 2005 (Hurtt et al., 2011; see also Table 4-2, Figure 4-2, Figure 4-3). In scenarios where cropland and pasture are projected to decrease, they are replaced with secondary vegetation. Tropical and boreal forest regions are both projected to undergo declining primary forest cover in most RCPs, but in RCP6.0 total forest area remains approximately constant and in RCP4.5 total forest area expands because of increased secondary forest. The extent to which primary vegetation is replaced by secondary vegetation, crops, or pasture varies between the RCPs (Figure 4-3), with no simple linear relationship between the extent of vegetation change and the level of total radiative forcing. Larger reductions in primary vegetation cover are projected in RCP8.5, owing to a general absence of proactive measures to control land cover change in that scenario. Large reductions are also projected in RCP2.6 owing to widespread conversion of land to biofuel crops (Figure 4-2). Smaller reductions are foreseen in RCP6.0 and RCP4.5, with the latter involving conservation of primary forest and afforestation as mitigation measures.

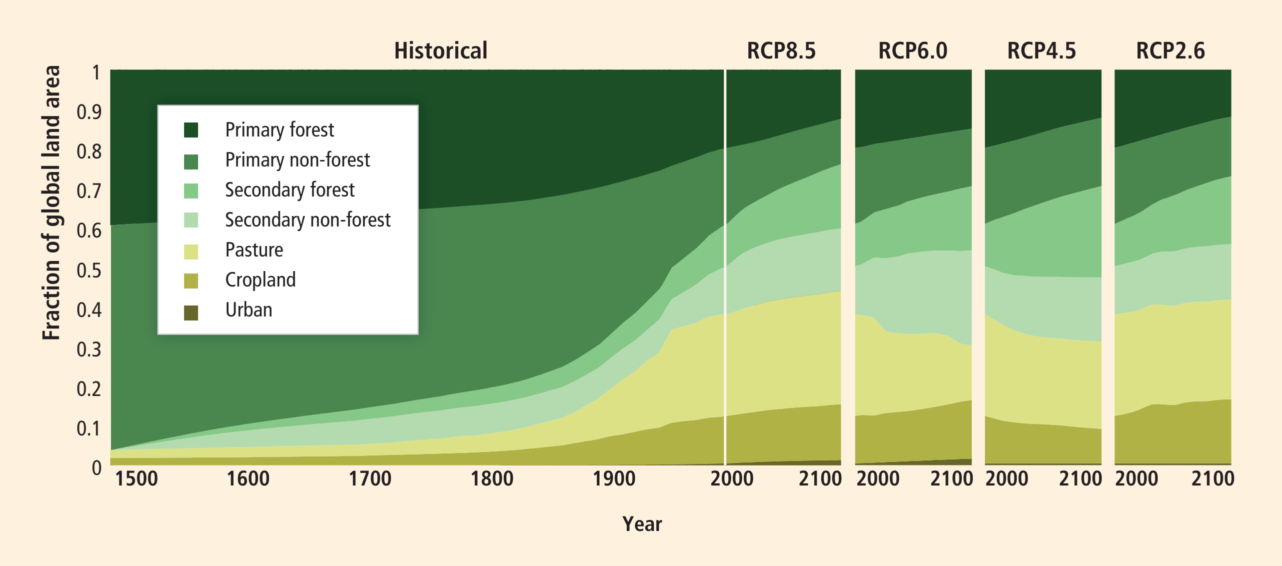

Figure 4-3 | Proportion of global land cover occupied by primary and secondary vegetation (forest and non-forest), cropland, pasture, and urban land, from satellite data and historical reconstructions up to 2005 (Klein Goldewijk et al., 2010, 2011), and from scenarios associated with the RCPs from 2005 to 2100 (Hurtt et al., 2011).

which can materially alter the net outcome of the land cover change on the global climate (*high confidence*).

4.2.4.2. Nitrogen Deposition

The global nitrogen cycle has been strongly perturbed by human activity over the past century (Gruber and Galloway, 2008; Canfield et al., 2010). Activities such as fertilizer production and fossil fuel burning currently transform 210 TgN yr^{-1} of nitrogen gas in the atmosphere into reactive forms of nitrogen (N_r) that can be readily used by plants and microorganisms in land and in the ocean, slightly more than the non-anthropogenic transformation of 203 TgN yr^{-1} (Fowler et al., 2013). Most of the transformations of anthropogenic N_r are on land (Fowler et al., 2013). The human-caused flow from land to oceans in rivers is 40 to 70 TgN yr^{-1}, additional to the estimated natural flux of 30 TgN yr^{-1} (Galloway et al., 2008; Fowler et al., 2013). Many of the sources of additional nitrogen share root causes with changes in the carbon cycle, such as increased use of fossil fuels and expansion and intensification of global agriculture. Nitrogen deposition, CO_2 concentrations, and temperatures are therefore increasing together at global scales (Steffen et al., 2011). Regional trends in nitrogen fluxes differ substantially: nitrogen fertilizer use and nitrogen deposition are stable or declining in some regions, such as Western Europe; but nitrogen deposition and its impacts on biodiversity and ecosystem functioning are projected to increase substantially over the next several decades in other regions, especially in the tropics (Galloway et al., 2008) owing to increased needs for food and energy for growing populations in emerging economies (e.g., Zhu et al., 2005).

Experiments and observations, most of which are in temperate and boreal Europe and North America, show a consistent pattern of increase in the dominance of a few nitrogen-loving plant species and loss of overall plant species richness at nitrogen deposition loads exceeding between 5 and 20 kgN ha^{-1} yr^{-1} (Power et al., 2006; Clark and Tilman, 2008; Bobbink et al., 2010; but see Stevens, C.J. et al., 2010). Nitrogen deposition is currently above these limits in much of Europe, eastern North America, and southern Asia (Galloway et al., 2008), including in many protected areas (Bleeker et al., 2011).

The impacts of nitrogen deposition are often first manifested in freshwater ecosystems because they collect and concentrate the excess nitrogen (and phosphorus) from the land, as well as from sewage and industrial effluents. Primary production in freshwater ecosystems can be either nitrogen and phosphorus limited or both (Elser et al., 2007), but the biodiversity and capacity of freshwater ecosystems to deliver high-quality water, recreational amenity, and fisheries services is severely reduced by the addition of nutrients beyond their capacity to process them. Excessive loading of nitrogen and phosphorus is widespread in the lakes of the Northern Hemisphere (NH; Bergström and Jansson, 2006), although reduced nitrogen loading including deposition was observed between 1988 and 2003 in Sweden (Weyhenmeyer et al., 2007). The observed symptoms include a shift from nitrogen limitation of phytoplankton in lakes to phosphorus limitation (Elser et al., 2009).

Since the AR4, an increasing number of studies have models, observations, and experiments to understand and predict the interactive effects of nitrogen deposition, climate change, and CO_2 on ecosystem function. Interactions between nitrogen and other global change factors are widespread, strong, and complex (Rustad, 2008; Thompson et al., 2008; Langley and Megonigal, 2010; Gaudnik et al., 2011; Eisenhauer et al., 2012; Hoover et al., 2012; but see Zavaleta et al., 2003, for evidence of additive effects). In a study of plant-pollinator relationships, the combination of nitrogen deposition, CO_2 enrichment, and warming resulted in larger negative impacts on pollinator populations than could be predicted from the individual effects (Hoover et al., 2012). In a perennial grassland species, nitrogen limitation constrained the response to rising CO_2 (Reich et al., 2006). Broadly, the overall body of research shows that ecosystem function is mediated by complex interactions between these factors, such that many ecosystem responses remain difficult to understand and predict (Churkina et al., 2010; Norby and Zak, 2011).

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In forests in many parts of the world, experiments, observations, and models suggest that the observed increase in productivity and carbon storage is due to combinations of nitrogen deposition, climate change, fertilization effects of rising CO_2, and forest management (Huang et al., 2007; Magnani et al., 2007; Pan et al., 2009; Churkina et al., 2010; Bellassen et al., 2011; Bontemps et al., 2011; de Vries and Posch, 2011; Eastaugh et al., 2011; Norby and Zak, 2011; Shanin et al., 2011; Lu et al., 2012). N deposition and rising CO_2 appear to have generally dominated in much of the NH. However, the direct effects of rising temperature and changes in precipitation may exceed nitrogen and CO_2 as key drivers of ecosystem primary productivity in a few decades time. In grasslands, however, experiments show that plant productivity is increased more by nitrogen addition (within the projected range for this century) than by elevated CO_2, also within its projected range, and that nitrogen effects increase with increasing precipitation (Lee et al., 2010).

In contrast to forests and temperate grasslands, nitrogen deposition and warming can have negative effects on productivity in other terrestrial ecosystems, such as moss-dominated ecosystems (Limpens et al., 2011). The interactions between nitrogen deposition and climate change remain difficult to understand and predict (Menge and Field, 2007; Ma et al., 2011), in part owing to shifts in plant species composition (Langley and Megonigal, 2010) and the complex dynamics of coupled carbon, nitrogen, and phosphorus cycles (Menge and Field, 2007; Niboyet et al., 2011).

Analyses using the multi-factor biodiversity change model GLOBIO3 suggest that nitrogen deposition will continue to be a significant contributing factor to terrestrial biodiversity loss in the first third of the 21st century but will be a less important factor than climate change in this period, and a much smaller driver than habitat loss due to expansion of agricultural lands (Alkemade et al., 2009). Models that explicitly take into account interactive effects of climate change and nitrogen deposition on plant communities project that nitrogen deposition impacts will continue to be important, but climate change effects will begin to dominate other factors by the middle of the 21st century (Belyazid et al., 2011).

4.2.4.3. Tropospheric Ozone

The concentration of ozone in the troposphere (the part of the atmosphere adjacent to the Earth's surface) has risen over the past 150 years from a global average of 20 to 30 ppb to 30 to 50 ppb, with high spatial and temporal variability (Horowitz, 2006; Oltmans et al., 2006; Cooper et al., 2010; WGI AR5 Figure 2.7). This is due to (1) increasing anthropogenic emissions of gases that react in the atmosphere to form ozone (Denman et al., 2007) and (2) the increased mixing of stratospheric ozone into the troposphere as a result of climate change (Hegglin and Shepherd, 2009). The key ozone precursor gases are volatile organic compounds (VOCs) and oxides of nitrogen (NO_x). Intercontinental transport of these precursors contributes to rising global background ozone concentrations, including in regions where local ozone precursor emissions are decreasing (Dentener et al., 2010). Global sources of VOC are predominantly biogenic (BVOC), especially forests (Hoyle et al., 2011).

Negative effects of the current levels of ozone have been widely documented (Mills et al., 2011). A meta-analysis of more than 300 articles addressing the effect of ozone on tree growth (Wittig et al., 2009)—focused largely on NH temperate and boreal species—concluded that current levels of tropospheric ozone suppress growth by 7% relative to preindustrial levels. Modeling studies that extrapolate experimentally measured dose-response relationships suggest a 14 to 23% contemporary reduction in Gross Primary Productivity (GPP) worldwide, with higher values in some regions (Sitch et al., 2007) and 1 to 16% reduction of Net Primary Productivity (NPP) in temperate forests (Ainsworth et al., 2012).

The mechanisms by which ozone (O_3) affects plant growth are now better known (Hayes et al., 2007; Ainsworth et al., 2012). Chronic exposure to O_3 at levels above about 40 ppb generally reduces stomatal conductance and impairs the activity of photosynthetic enzymes (The Royal Society, 2008), although in some cases ozone exposure increases stomatal conductance (Wilkinson and Davies, 2010). For the species studied, carbon assimilation rates and leaf area are generally reduced, while respiration increases and leaf senescence is accelerated—all leading to a reduction in NPP. Conifers are less sensitive than broad-leafed species. In a modeling study, lower stomatal conductance due to O_3 exposure increased river runoff by reducing the loss of soil moisture through transpiration, but observational studies that measured runoff in relation to ozone exposure show divergent trends on this issue (McLaughlin et al., 2007; Wittig et al., 2007; Mills et al., 2009; Huntingford et al., 2011).

A modeling study (Sitch et al., 2007) suggests that the negative effects of rising O_3 on plant productivity could offset 17 to 31% of the projected increase in global carbon storage due to increasing CO_2 concentrations over the 21st century, but the possible interactive effects between CO_2 and O_3 are poorly understood (The Royal Society, 2008). Reduced stomatal conductance, widely observed under elevated CO_2, should help protect plants from ozone damage. Some chamber experiments (Bernacchi et al., 2006) and model studies (Klingberg et al., 2011) suggest this to be the case. The one plot-scale study of CO_2 and O_3 interactions in a temperate forest (Karnosky et al., 2005; Hofmockel et al., 2011) suggests that the effects of O_3 and CO_2 are not independent and may partly compensate for one another.

There is genotypic variation in plant sensitivity to O_3 (Ainsworth et al., 2012). Other than changing cultivars or species, few management actions promoting adaptation to higher levels of O_3 are currently available (Wilkinson and Davies, 2010; Teixiera et al., 2011). Research into developing ozone resistant varieties and chemical protectants against damage may provide management options in the future (Wilkinson and Davies, 2010; Ainsworth et al., 2012).

4.2.4.4. Rising Carbon Dioxide

Rising atmospheric CO_2 concentrations affect ecosystems directly and through biological and chemical processes. The consequences for the global carbon cycle are discussed in WGI AR5 Box 6.3; the discussion here focusses on impacts on terrestrial and inland water systems. Paleo records over the Late Quaternary (past Myr) show that changes in the atmospheric CO_2 content between 180 and 280 ppmv had ecosystem-scale effects worldwide (Prentice and Harrison, 2009).

In contrast to the oceans, changes in CO_2 concentrations in inland waters are influenced primarily by biological processes, such as inputs of terrestrial organic matter, particularly dissolved organic carbon (DOC), and bacterial respiration (van de Waal et al., 2010; Aufdenkampe et al., 2011). Carbon can, however, become limiting during intense algal blooms, especially in the surface waters of stratified lakes and reservoirs, and rising atmospheric CO_2 concentrations may stimulate higher algal production under these conditions (van de Waal et al., 2010). Higher CO_2 concentrations can lead to increases in the C:N and C:P ratios of phytoplankton, though the trophic consequences of this are difficult to predict because zooplankton may alter their feeding behavior to select higher quality forms of algae or increase feeding rate (Urabe et al., 2003; van de Waal et al., 2010).

Over the past 2 decades, and especially since AR4, experimental investigation of elevated CO_2 effects on plants and ecosystems has used mainly Free Air CO_2 Enrichment (FACE) techniques (Leakey et al., 2009). FACE is considered more realistic than earlier approaches using enclosed chambers, because plant community and atmospheric interactions and below-ground conditions are more like those of natural systems. Plants with a C_3 photosynthetic system, which includes most species but excludes warm-region grasses, show an increase in photosynthesis under elevated CO_2, the precise magnitude of which varies between species. Acclimation ("down-regulation") occurs under long-term exposure, leading to cessation of effects in some (Norby and Zak, 2011) but not all studies (Leakey et al., 2009). The C_4 photosynthetic system found in most tropical grasses and some important crops is not directly affected by elevated CO_2, but C_4 plant productivity generally increases under elevated CO_2 because of increased water use efficiency (WUE). Transpiration is decreased under elevated CO_2 in many species, due to reduced opening of stomatal apertures, leading to greater WUE (Leakey et al., 2009; Leuzinger and Körner, 2010; De Kauwe et al., 2013). Increasing WUE is corroborated by studies of stable carbon isotopes (Barbosa et al., 2010; Koehler et al., 2010; Silva et al., 2010; Maseyk et al., 2011). The WUE increase does not acclimate to higher CO_2 in the medium term, that is, over several years (Leakey et al., 2009). Satellite observations from 1982–2010 show an 11% increase in green foliage cover in warm, arid environments (where WUE is most important) after correcting for the effects of precipitation variability (Donohue et al., 2013); gas exchange theory predicts 5 to 10% greening resulting from rising CO_2 over this period.

The interactive effects of elevated CO_2 and other global changes (such as climate change, nitrogen deposition, and biodiversity loss) on ecosystem function are extremely complex. Generally, nitrogen use efficiency is

Frequently Asked Questions

FAQ 4.2 | What are the non–greenhouse gas effects of rising carbon dioxide on ecosystems?

Carbon dioxide (CO_2) is an essential building block of the process of photosynthesis. Simply put, plants use sunlight and water to convert CO_2 into energy. Higher CO_2 concentrations enhance photosynthesis and growth (up to a point), and reduce the water used by the plant. This means that water remains longer in the soil or recharges rivers and aquifers. These effects are mostly beneficial; however, high CO_2 also has negative effects, in addition to causing global warming. High CO_2 levels cause the nitrogen content of forest vegetation to decline and can increase their chemical defenses, reducing their quality as a source of food for plant-eating animals. Furthermore, rising CO_2 causes ocean waters to become acidic (see FAQ 6.3), and can stimulate more intense algal blooms in lakes and reservoirs.

increased under higher CO_2 (Leakey et al., 2009) although, in some tree FACE experiments, productivity increases as a result of enhanced CO_2 if sustained by increased nitrogen uptake rather than increased nitrogen use efficiency (Finzi et al., 2007). In one 10-year temperate grassland experiment in Minnesota, elevated CO_2 halved the loss of species richness expected from nitrogen addition (Reich, 2009), whereas no such benefit was reported for an alpine grassland in France (Bloor et al., 2010) or a Danish heathland ecosystem (Kongstad et al., 2012).

Elevated CO_2 can affect plant response to other stresses, such as high temperature (Lloyd and Farquhar, 2008) and drought. Ozone exposure decreases with lower stomatal conductance (Sitch et al., 2007). In savannas, faster growth rates under higher CO_2 can allow woody plants to grow tall enough between successive fires to escape the flames (Bond and Midgley, 2001; Scheiter and Higgins, 2009). Differential species responses to elevated CO_2 appear to be altering competition (Dawes et al., 2011), for example, increasing the likelihood of faster-growing species such as lianas out-competing slower-growing species such as trees (Mohan et al., 2006; Potvin et al., 2007; Lewis et al., 2009a).

Experimental studies have shown that elevated CO_2 leads to increased leaf C:N ratios in woody plants, forbs, and C_3 grasses (but not C_4 grasses), which may decrease their quality as food and increase herbivorous insect feeding rates and changes to their density and community structure (Sardans et al., 2012). Plants may also become more toxic to herbivores under elevated CO_2 levels, through increased concentrations of carbon- and nitrogen-based defenses (Lindroth, 2010; Cavagnaro et al., 2011).

Our understanding of ecosystem responses to elevated CO_2 is incomplete in some respects. The majority of FACE experiments apply upper CO_2 concentrations of approximately 550 ppmv, which is below the concentrations projected by 2100 under higher emissions scenarios. The physiology of photosynthesis suggests that direct CO_2 effects saturate at levels of approximately 700 ppmv (Long et al., 2004). Most elevated CO_2 experiments impose a sudden increase of CO_2 concentration as opposed to the gradual rise experienced in reality. Most large-scale FACE experiments have been conducted in temperate locations (e.g., Hickler et al., 2008); there are currently no large-scale tropical or boreal FACE experiments. The magnitude of CO_2 effects decreases as the spatial scale of study increases (Leuzinger et al., 2011).The scale of controlled experiments is limited to approximately 100 m^2. Extrapolation to larger scales ignores large-scale atmospheric feedbacks (Körner et al., 2007) and catchment-scale hydrological effects (see Box CC-VW). Overall, there is *medium confidence* (*much evidence*, *medium agreement*) that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water use efficiency, but at a diminishing rate.

CO_2 effects are a first-order influence on model projections of ecosystem and hydrological responses to anthropogenic climate change (Sitch et al., 2008; Lapola et al., 2009; Friend et al., 2013).The direct effect of CO_2 on plant physiology, independent of its role as a GHG, means that assessing climate change impacts on ecosystems and hydrology solely in terms of global mean temperature rise (or equivalently, expressing GHG effects solely in terms of radiative forcing) is an oversimplification (Huntingford et al., 2011; Betts et al., 2012). A 2°C rise in global mean temperature, for example, may have a different net impact on ecosystems depending on the change in CO_2 concentration accompanying the rise (e.g., Good et al., 2011a). A high climate sensitivity and/or a higher proportion of non-CO_2 GHGs would imply a relatively low CO_2 rise at 2°C global warming, so the offsetting effects of CO_2 fertilization and increased water use efficiency would be smaller than for low climate sensitivity and/or a lower proportion of non-CO_2 GHGs.

4.2.4.5. Diffuse and Direct Radiation

The quantity and size distribution of aerosols in the atmosphere alters both the amount of solar radiation reaching the Earth's surface and the proportions of direct versus diffuse radiation. In some regions, direct radiation has been reduced by up to 30 W m^{-2} over the industrial era, with an accompanying increase in diffuse radiation of up to 20 W m^{-2} (Kvalevåg and Myhre, 2007). The global mean direct and diffuse radiation changes due to aerosols are –3.3 and +0.9 W m^{-2}, respectively (Kvalevåg and Myhre, 2007). For a constant total radiation, an increased fraction received as diffuse radiation theoretically increases net photosynthesis because a smaller fraction of the vegetation canopy is light-saturated, making photosynthesis more light efficient at the canopy scale (Knohl and Baldocchi, 2008; Kanniah et al., 2012). In a global model that included this effect, an increase in diffuse fraction of solar radiation due to volcanic and anthropogenic aerosols and cloud cover was simulated to lead to approximately a 25% increase in the strength of the global land carbon sink between 1960 and 1999; however, under a scenario of climate change and decreased anthropogenic aerosol concentration, this enhancement declined to near zero by the end of the 21st century (Mercado et al., 2009), All RCPs project decreased aerosol concentrations due to air quality protection measures, as already seen in some countries. The influence of the form of radiation on plant growth and the land carbon budget is a potentially important unintended consequence of solar radiation management schemes that involve the injection of aerosols into the stratosphere to reduce radiant forcing (see WGI AR5 Section 7.7), but this topic is at present insufficiently researched for adequate assessment.

4.2.4.6. Invasive and Alien Species

Since the IPCC AR4, the number of observations of the spread and establishment of alien species attributed to climate change has increased for several taxa (e.g., Walther et al., 2009) and for particular areas, including mountain tops and polar regions (McDougall et al., 2011; Chown et al., 2012). Species invasions have increased over the last several decades (*very high confidence*), and the aggressive expansion of plant and animal species beyond their historical range is having increasingly negative impacts on ecosystem services and biodiversity (*high confidence*; Brook, 2008; Burton et al., 2010; McGeoch et al., 2010; Simberloff et al., 2013). Climate change will exacerbate some invasion impacts and ameliorate others (Peterson et al., 2008; Bradley et al., 2009; Britton et al., 2010; Bellard et al., 2013). Although there is increasing evidence that some species invasions have been assisted by climate change, there is *low confidence* that species invasions have in general been assisted by recent climatic trends because of the overwhelming importance of human-facilitated dispersal in mediating invasions. The spread of alien species has several causes, including habitats made favorable by climate change (Walther et al., 2009), deliberate species

Frequently Asked Questions

FAQ 4.3 | Will the number of invasive alien species increase as a result of climate change?

Some invasive plants and insects have already been shown to benefit from climate change and will establish and spread into new regions (where they are "aliens"), once they are introduced. The number of newly arrived species and the abundance of some already established alien species will increase because climate change will improve conditions for them. At the same time, increasing movement of people and goods in the modern world, combined with land use changes worldwide, increases the likelihood that alien species are accidentally transported to new locations and become established there. There are many actions that can be taken to reduce, but not eliminate, the risk of alien species invasions, such as the treatment of ballast water in cargo ships and wood products, strict quarantine applied to crop and horticultural products, and embargos on the trade and deliberate introduction of known invader species. Some invasive species will suffer from climate change and are expected to decrease in range and population size in some regions. Generally, increased establishment success and spread will be most visible for those alien species that have characteristics favored by the changing climate, such as those that are drought tolerant or able to take advantage of higher temperatures.

transfer, and accidental transfer due to increased global movement of goods.

In most cases climate change increases the likelihood of the establishment, growth, spread, and survival of invasive species populations (Dukes et al., 2009; Walther et al., 2009; Bradley et al., 2010; Huang et al., 2011; Chown et al., 2012). Some degree of climate/habitat match has been found to be a prerequisite of establishment success across seven major plant and animal groups (Hayes and Barry, 2008). A range of alien species responses and local consequences are expected (e.g., Rahel and Olden, 2008; Frelich et al., 2012; Haider et al., 2012; West et al., 2012). Invasive species, compared to native species, may have traits that favor their survival, reproduction, and adaptation under changing climates; invasive plants in particular tend to have faster growth rates and are particularly favored when resources are not limited (*medium* to *high confidence*; van Kleunen et al., 2010; Willis, C.G. et al., 2010; Buswell et al., 2011; Davidson et al., 2011; Zerebecki and Sorte, 2011; Haider et al., 2012; Matzek, 2012). Some invasive plants are more drought tolerant (Crous et al., 2012; Matzek, 2012; Perry et al., 2012), and on average they have higher overall metabolic rates, foliar nitrogen concentrations, and photosynthetic rates than their native counterparts (Leishman et al., 2007).

Extreme climate events provide opportunities for invasion by generating disturbances and redistributing available resources (Diez et al., 2012) and changing connectivity between different ecosystems. Current warming has already enabled many invasive alien species, including plant, vertebrate, invertebrate, and single-cell taxa, to extend their distributions into new areas (*high confidence* for plants and insects; Walther et al., 2009; Smith et al., 2012). However, population declines and range contractions are predicted for some invasive species in parts of their ranges (Bradley et al., 2009; Sobek-Swant et al., 2012; Taylor et al., 2012; Bertelsmeier et al., 2013). The expansion of invasive species in some areas and contraction in others will contribute to community reorganization and the formation of novel ecosystems and interactions in both terrestrial and freshwater habitats (*high confidence*; e.g., Britton et al., 2010; Kiesecker, 2011; Martinez, 2012; see also Section 4.3.2.5). For example, invasive grasses may be favored over native ones with increasing temperatures (Parker-Allie et al., 2009; Chuine et al., 2012; Sandel and Dangremond, 2012).

In a few cases, benefits to biodiversity and society may result from the interactive effects of climate change and invasive species, such as increases in resources available to some threatened species (Caldow et al., 2007), forest structural recovery (Bolte and Degen, 2010), and available biomass for timber and fuel (van Wilgen and Richardson, 2012). The effect of invasions on net changes in carbon stocks are situation specific and may be either positive or negative (Williams, A.L. et al., 2007). Rising CO_2 levels will increase the growth rates of most invasive plant species (Mainka and Howard, 2010; but see Section 4.2.4.4).The effectiveness of invasive alien species management for sequestering carbon is uncertain and context specific (Peltzer et al., 2010). Longer term, indirect effects of invasive alien species will be more important than direct, short-term effects, for instance, as a result of changes in soil carbon stocks and tree community composition (*low* to *medium confidence*; Peltzer et al., 2010).

Synergistic interactions occur between climate change and invasive alien species, along with landscape change, habitat disturbance, and human-facilitated breakdown of dispersal barriers (Brook et al., 2008; Angeler and Goedkoop, 2010; Bradley et al., 2010; Winder, M. et al., 2011). Climate change and invasive alien plant species generally increase the risk and intensity of fire, and the interaction is being reported more frequently as a direct result of higher temperatures and increased invasive plant biomass (*high confidence*; Abatzoglou and Kolden, 2011). In freshwater systems, alien species establishment and survival, species interactions, and disease virulence will change as a result of changes in frequency of high-flow events, increasing water temperature, water properties, and water demand (*medium confidence*; Schnitzler et al., 2007; Rahel and Olden, 2008; Britton et al., 2010).

A range of climate change-related variables (extreme events and changes in precipitation, temperature, and CO_2) will continue to exacerbate the establishment and spread of pests, vectors, and pathogens and negatively impact production systems (*medium confidence*; Robinet and Roques, 2010; Clements and Ditommaso, 2011). Warming has contributed to the spread of many invasive insect species, such as the mountain pine

4

bark beetle, and resulted in forest destruction (*high confidence*; Raffa et al., 2008). The interactions between crop growth, climate change, and pest or pathogen dynamics are difficult to predict (West et al., 2012). Management strategies may become less effective as a consequence of the decoupling of biocontrol relationships and less effective mechanical control as biomass and/or population size of invasive species increases (*low* to *medium confidence*; Hellmann et al., 2008).

4.3. Vulnerability of Terrestrial and Freshwater Ecosystems to Climate Change

The vulnerability of ecosystems to climate change, that is, their propensity to be adversely affected, is determined by the sensitivity of ecosystem processes to the particular elements of climate undergoing change and the degree to which the system (including its coupled social elements) can maintain its structure, composition, and function in the presence of such change, either by tolerating or adapting to it. Tolerance and adaptability both interact with exposure, which in the case of terrestrial and freshwater ecosystems means the magnitude and rate of climate change relative to ranges of climatic conditions and rates of change under which the ecosystem developed and its organisms evolved. Chapter 19 provides a full discussion on vulnerability concepts.

4.3.1. Changes in the Disturbance Regime

The species composition at a given location is determined by three considerations: the ability of species to reach the location; the physiological tolerance of the species in relation to the range of conditions experienced there; and interactions with other species, including competitors, symbionts, predators, prey, and pathogens. Occasional disturbances relieve competition, create opportunities for the establishment and success of less dominant species, and may facilitate dispersal. Moderate disturbance is thus important in maintaining diversity and ecosystem function (Connell, 1978). Exposure to disturbances keeps tolerance of disturbance in the population high. Fire, floods, and strong winds are all examples of biodiversity-sustaining climate disturbances, provided that their frequency and intensity do not deviate greatly above or below the regime to which the species are adapted. Average environmental conditions may be less of a determinant of species range and abundance than the extreme conditions, such as the occurrence of exceptionally cold or hot days or droughts exceeding a certain duration (Zimmermann et al., 2009). The projected changes in probability of extremes are typically disproportionately larger than the projected changes in the mean (see IPCC, 2012; but also Diffenbaugh et al., 2005). Biotic disturbances, such as pest and pathogen outbreaks are also often implicated in ecosystem change, and may be enabled by climate change.

It is suggested that ecosystem regime shifts resulting from climate change (alone or in interaction with other factors) will often be triggered by changes in the disturbance regime, rather than by physiological tolerance for the mean conditions (Thonicke et al., 2001). A "disturbance regime" refers to the totality of different types of disturbance events in a system, each characterized by its probability of occurrence, intensity, and other relevant attributes, such as its seasonal pattern. A corollary is that disturbance-related change is abrupt rather than gradual. Change in the fire disturbance regime is emerging as a key proximal mechanism and early indicator of terrestrial ecosystem change (Girardin et al., 2009; Johnstone et al., 2010). Changes in the fire regime have in some cases been attributed to climate change (Littell et al., 2009). Regional trends in fire occurrence have been observed since 2000 (Giglio et al., 2013), but interpreting their significance requires a longer term perspective (e.g., Bergeron et al., 2010).

4.3.2. Observed and Projected Change in Ecosystems

This section highlights key observed changes in terrestrial and freshwater ecosystems over the recent past, as well as changes projected during the 21st century. For observations, we assess the degree of confidence that change has been detected, and separately the confidence we have in attributing the change to climate change (Figure 4-4). Confidence in detection is considered to be *very high* when there is *high agreement* between many independent studies, species, ecosystems, or regions and where there is *robust evidence* that the changes over time are statistically significant (see Chapter 18; Mastrandrea et al., 2010). Note that a slightly different definition of detection is used here than in Chapter 18, because detection here is based solely on the presence of a temporal trend and does not attempt to distinguish natural from climate-related variation. Confidence in attribution to climate change is *very high* when three tests are satisfied: changes correspond to a sound mechanistic understanding of responses to climate change; the time series of observations is sufficiently long to detect trends correlated with climate change; and confounding factors can be accounted for or are of limited importance. In the sections that provide the details of the assessment of detection and attribution, estimated levels of confidence are given even in cases where the capacity for detection or attribution capacity is *low* or *very low*, because changes in these ecosystem properties or processes could have large impacts on biodiversity or ecosystem services at regional to global scales. In all cases the estimates of confidence levels are based on global and cross-taxon assessments, so the positioning may be different for specific taxa or regions. Some of the sections include assessments of model-based projections of future change; the confidence assessment of detection and attribution does not extend to these.

A key message arising from the analysis of *detection* and *attribution* is that climate impacts on the functioning of organisms and ecosystems are clearest when temperature is a principal driver, changes are relatively rapid, and confounding factors play a small role. At one end of the spectrum, the large warming signal over the last several decades in much of the Arctic tundra combined with minimal human impacts is associated with *high confidence* in detection of an increase in shrubs and permafrost thawing and *high confidence* in the attribution to climate warming (Section 4.3.3.1.1). Likewise, the phenology of most organisms is sensitive to temperature, confounding effects are often small, and the response is rapid, leading to *high confidence* in detection and attribution of changes in phenology to warming (Section 4.3.2.1). At the opposite end of the spectrum, species extinctions are very difficult to attribute to climate change (Section 4.3.2.5), in part because other factors dominate recent extinctions. This does not mean that climate has not played an important contributing role; indeed it has been argued that the low level of confidence in attribution is due to the lack of studies looking for climate signals in extinctions (Cahill et al., 2013). Similarly there is

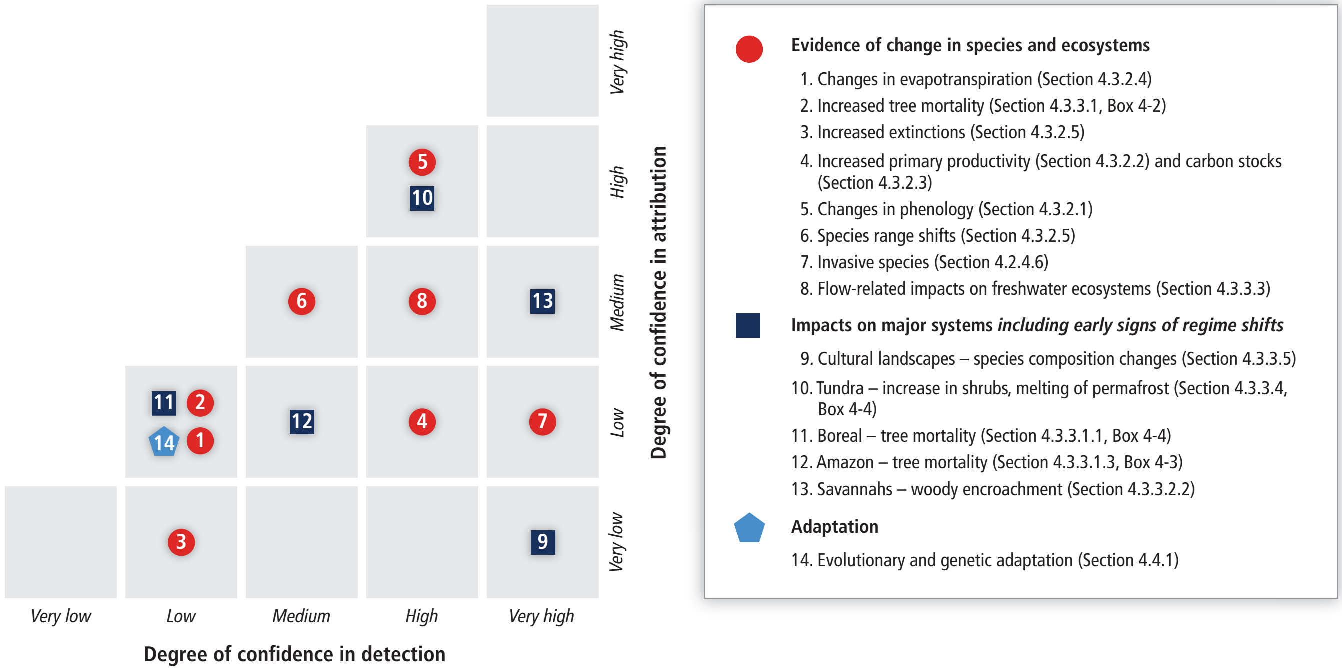

Figure 4-4 | Confidence in detection of change and attribution of observed responses of terrestrial ecosystems to climate change. Confidence levels are based on expert judgment of the available literature following the IPCC uncertainty guidance (Mastrandrea et al., 2010), attribution criteria outlined in Chapter 18, and detection criteria defined in the text. The symbols in the figure represent global and cross-taxon assessments; the positioning may be different for specific taxa or regions. Details of the assessments that were used in positioning each of the points can be found in the sections given in parentheses.

very good evidence that species composition is changing in cultural landscapes, but the important role of other factors, for example, land management and nitrogen deposition, makes attribution of a contribution to recent warming difficult. This analysis indicates that responses in most species and ecosystem levels will become more apparent over time because (1) observed organism-level changes will have long-term impacts on ecosystem functioning (*high confidence*; Sections 4.3.2.1, 4.3.2.5, 4.3.3) and (2) warming signals can be detected in ecosystems where the recent warming has been strong and confounding factors are minimal. In addition, the absence of observed changes does not preclude confident projections of future change for three reasons: climate change projected for the 21st century substantially exceeds the changes experienced over the past century in medium to high scenarios (all but RCP2.6); ecosystem responses to climate change may be nonlinear; and change may be apparent only after considerable time lags (Jones et al., 2009).

4.3.2.1. Phenology

Further evidence from ground-based and satellite studies, focused mainly on the NH (Northern Hemisphere), supports the AR4 conclusion that shifts in phenology have occurred over recent decades. "Spring advancement"—earlier occurrence of spring events, such as breeding, bud burst, breaking hibernation, flowering, migration—is seen in hundreds of plant and animal species in many regions (Menzel et al., 2006; Cleland et al., 2007; Parmesan, 2007; Primack et al., 2009; Cook et al., 2012a; Peñuelas et al., 2013), although magnitudes of change vary considerably and some species show no change (Parmesan, 2007). Apparent discrepancies between two estimates of overall NH spring advancement noted in AR4 (-2.3 days per decade, Parmesan and Yohe, 2003; -5.1 days per decade, Root et al., 2003) are largely resolved when methodological differences are accounted for, particularly the inclusion of species that do not show phenological changes (Parmesan, 2007). A combined analysis of 203 species suggests NH spring advancement of -2.8 ± 0.35 days per decade (Parmesan, 2007).

4.3.2.1.1. Plants

Spring advancement is seen across the NH including North America (e.g., Cook et al., 2008, 2012b), Europe (e.g., Menzel et al., 2006; Cook et al., 2012b), Asia (e.g., Primack et al., 2009; Ma and Zhou, 2012), and the High Arctic (Høye et al., 2007). Changes are generally larger at higher latitudes. A meta-analysis indicates mean NH spring advancement of -1.1 ± 0.16 days per decade for herbs and grasses (85 species), -1.1 ± 0.68 days per decade for shrubs (6 species), and -3.3 ± 0.87 days per decade for trees (16 species), over a record period of 35 to 132 years, depending on the study. The warming trends detected in the well-mixed surface waters (epilimnion) of many lakes in North America, Eurasia, and Africa (Adrian et al., 2009) are associated with the earlier onset of spring phytoplankton blooms (Winder and Schindler, 2004; Winder and Sommer, 2012). Satellite data also indicate a general tendency of spring advancement, though there is variation between satellite studies, especially at local scales, due to the use of different instruments and methods (e.g., White et al., 2009). A study using the Advanced Very High Resolution Radiometer (AVHRR) suggests that for vegetation between 30°N and 80°N, the start of the growing season advanced by -5.2 days between 1999 and 1982 and advanced a further -0.2 days by 2008; while the growing season end was delayed by 6.6 days between 1982 and 2008 (Jeong et al., 2011). Studies with a more recent satellite instrument, the Moderate Resolution Imaging Spectrometer (MODIS), also show spring advancement (e.g., Ahl et al., 2006). The relatively short duration of satellite observations makes trend detection particularly sensitive to the choice of analysis period.

4.3.2.1.2. Animals

Many new studies provide further evidence of changes in animal phenology (e.g., amphibians: Kusano and Inoue, 2008; Phillimore et al., 2010; birds: Pulido, 2007; Thorup et al., 2007; mammals: Adamik and Kral, 2008; Lane et al., 2012; insects: Robinet and Roques, 2010; freshwater plankton: Adrian et al., 2009). Changes in breeding phenology are reported from various regions and different taxa (e.g., Parmesan, 2006, 2007; Post et al., 2008; Primack et al., 2009). In the NH several studies show advancements of egg laying dates in birds (e.g., Parmesan, 2007: -3.7 ± 0.7 days per decade, in 41 species). In contrast, a delay of the mean breeding date by 2.8 to 3.7 days between 1950 and 2004 was seen for two of nine seabirds in the Eastern Antarctic, linked to decreased sea ice extent (Barbraud and Weimerskirch, 2006). Spring arrival dates have advanced for many migratory birds (e.g., Thorup et al., 2007). Patterns of changes in autumn migration in birds are mostly not consistent (delayed, advanced, no change) across analyzed species and regions and appear to be highly related to non-climatic variables (e.g., Sokolov, 2006; Adamik and Pietruszkova, 2008).

A large body of evidence therefore shows that, in NH temperate, boreal, and Arctic regions, spring advancement has occurred in many plant and animal species over the last several decades (*high confidence* due to *robust evidence* but only *medium agreement* when examined across all species and regions; Figure 4-4).

Understanding of the drivers of phenological change has also improved further since AR4. Many observational studies find a correlation with higher temperatures (Cook et al., 2012a). Experimental manipulation generally supports this (e.g., plants: Cleland et al., 2012; bird egg-laying: Visser et al., 2009; insects: Musolin et al., 2010; Kollberg et al., 2013). Some individual studies find good agreement between experimental warming and *in situ* observations (e.g., Gunderson et al., 2012) although a meta-analysis suggests that experiments can substantially under-predict advances in the timing of flowering and leafing of plants in comparison with observational studies (Wolkovich et al., 2012). Observational data can also be affected by methodological issues; for example, flipper-tagging of penguins can alter their migratory behavior (Saraux et al., 2011). Rates of warming across a season may also be important (Schaper et al., 2012). Models can be used to explain relationships between observed phenological changes and environmental variables. For example, a model based on water temperature captured the observed temporal and spatial variation in *Daphnia* phenology in NH lakes (Straile et al., 2012). Other environmental factors related to temperature, such as timing of snowmelt, snow cover, and snow depth, can play a role. Snowmelt changes led to earlier flowering and appearances of plants and arthropods in Greenland between 1996 and 2005 (Høye et al., 2007) and earlier flowering in an alpine plant in the Rocky Mountains, USA, between 1975 and 2008 (Hülber et al., 2010; Lambert et al., 2010). Earlier snowmelts decreased floral resources and hence affected insect population dynamics in mountain ranges in the USA in the years 1980, 1985, 1986, and 1989 (Boggs and Inouye, 2012). In Colorado, USA, the yellow-bellied marmot emerged earlier from hibernation due to snowmelts becoming earlier over 1976–2008 (Ozgul et al., 2010) while in Alberta, Canada, Columbian ground squirrels emerged later over 1992–2012 owing to delayed snowmelts associated with increased late-season snowstorms (Lane et al., 2012). Delayed emergence from hibernation was associated with decreased population growth rate (Lane et al., 2012). Food availability can be important; for example, in the Yukon area, Canada, the date of giving birth in North American squirrels (*Tamiascurus hudsonicus*) advanced by an average of -18 days over the period 1989–1998, coinciding with increasing abundance of white spruce cones, their major food source (Réale et al., 2003).

Phenological response can differ with migration strategy in birds, for example short-distance migrants show greater advancements in spring arrivals than long distant migrants (e.g., Saino et al., 2009; but see Parmesan, 2006 for different patterns). In a temperate region (Massachusetts, USA), declining sizes of populations and migrating cohorts of North American Passerine birds account for a large part of the variation in migration times between 1970 and 2002 (Miller-Rushing et al., 2008). The remaining variation was explained by climatic variables, migration distance, and date. The variation in bird migration phenology change can also be related to differing patterns of feather changes during moulting times, food availability at stop-over places, and differing health conditions of individual species (Gordo, 2007).

Although a number of non-climatic influences on phenology are also identified, an increased number of observational and experimental studies, across many organism types, suggest that warming has contributed to the overall spring advancement observed in the NH (*high confidence* due to *high agreement* and *medium evidence*).

4.3.2.2. Primary Productivity

Primary production, the process of plant growth, is fundamental to the global carbon cycle (see Section 4.3.2.3) and underpins provisioning ecosystem services such as food, timber, and grazing. Trends in the amount, seasonal timing, variability, location, and type of primary production are therefore important indicators of ecosystem function. Well-established theory, experimentation, and observation all agree that primary production is directly sensitive to most aspects of climate change, is indirectly affected via the effects of climate on pests and diseases, and is responsive to many of the other changes simultaneously taking place in the world, such as described in Section 4.2.4. The diverse and frequently nonlinear form of responses to the factors influencing primary production, combined with the complexity of interactions between them, means that at a given location the net outcome can be an increase, no change, or a decrease in productivity.

The concentration of CO_2 in the atmosphere shows clear patterns in space and time largely related to the primary productivity of the land and oceans. The contribution by terrestrial ecosystems to these patterns can be estimated using isotope measurements, emission databases, and models (Canadell et al., 2007). It consists of a sink term, due to increased net ecosystem production, plus a source term due to land use change. During the decade 2000–2009, land net primary productivity at the global scale continued to be enhanced about 5% relative to the estimated preindustrial level, leading to a land sink of 2.6 + 1.2 PgC yr^{-1} (these values are from WGI AR5 Section 6.3.2.6; the uncertainty range is 2 standard deviations; for the primary literature see also Raupach et al., 2008; Le Quéré et al., 2009). The net uptake of carbon by the land is highly variable year to year, mainly in response to climate variation and major volcanic eruptions (Peylin et al., 2005; Sitch et al., 2008; Mercado et al., 2009). Given the uncertainty range, it is not possible to conclude whether the rate of carbon uptake by the residual land sink has increased or decreased over the past 2 decades (Raupach et al., 2008; WGI AR5 Section 6.3.2.6). Coupled Model Intercomparison Project Phase 5 (CMIP5) model projections, using the RCP scenarios, suggest that the rate of net carbon uptake by terrestrial ecosystems will decrease during the 21st century except under the RCP4.5 scenario, and by the greatest amount under RCP8.5. There is greater uncertainty between models than between scenarios; in some models terrestrial ecosystems become a net source of CO_2 to the atmosphere (WGI AR5 Section 6.4.3.2, especially Figure 6.26).

It is possible to downscale the land sink estimate continentally, using inversion modeling techniques and the growing network of precision atmospheric observations. There is *high agreement* and *medium evidence* that the net land uptake in natural and semi-natural terrestrial ecosystems is broadly distributed around the world, almost equally between forested and non-forested ecosystems, but is offset in the tropics by a large carbon emission flux resulting from land use change, principally deforestation (Pan et al., 2011).

The observed trends in Normalized Difference Vegetation Index (NDVI), a satellite proxy for primary productivity, are discussed under various ecosystem-specific discussions above and below. In some cases the trends are sufficiently strong and consistent to support a confident statement about the underlying phenomenon, but in many cases they are not. This may mean that no change has occurred, or simply reflect inadequacies in the indicator, method of analysis, and length of the record in relation to the high interannual variability. AR4 reported a trend of increasing seasonally accumulated NDVI ("greening") at high northern latitudes (Fischlin et al., 2007; based on Sitch et al., 2007), but subsequent observations show a lower rate and no geographical uniformity (Goetz et al., 2007). More than 25% of high-latitude North American forest areas, excluding areas recently disturbed by fire, showed a decline in greenness and no systematic change in growing season length, particularly after 2000 (Goetz et al., 2007). NDVI trend analyses in rangelands show varying patterns around the world, with substantial disagreement between studies (Millennium Ecosystem Assessment, 2005a; Bai et al., 2008; Beck, H.E. et al., 2011; Fensholt et al., 2012). There is agreement that the Sahel showed widespread NDVI increase between the mid-1980s and about 2000, along with an increase in rainfall, but no consensus on whether the detected signal represents increased productivity by grasses, trees, or herbs; and to what degree it reveals land management efforts or responses to climate (Anyamba and Tucker, 2005; Prince et al., 2007; Hellden and Tottrup, 2008; Seaquist et al., 2009). In the period 2000–2009 no NDVI trend was apparent in the Sahel (Samanta et al., 2011).

Tree rings record changes in tree growth over approximately the past millennium. Many tree ring records show accelerated tree growth during much of the 20th century (Briffa et al., 2008), which often correlates with rising temperature. Variations in tree ring width, density, and isotopic composition arise from many factors, including temperature, moisture stress, CO_2 fertilization, N deposition, and O_3 damage, but also stand structure and management. Direct CO_2 effects, inferred from the ring record once the effects of drought and temperature have been accounted for, have been proposed for approximately 20% of the sites in the International Tree Ring Data Base (Gedalof and Berg, 2010) and studied in detail at some sites (Koutavas, 2008). Since the 1980s, a number of tree ring records show a decline in tree growth (Wilson et al., 2007). Several possible causes have been suggested for this, including increasing water stress and O_3 damage; but the most recent rings in most published tree ring chronologies date from before the 1990s (Gedalof and Berg, 2010), so tree ring-based conclusions for the past 2 decades are based on a relatively small body of evidence and may therefore be biased. Recent tree ring studies were often specifically designed to examine growth in response to environmental changes (Gedalof and Berg, 2010) and may therefore not be representative of global tree growth. Direct repeated measurements of tree girth increment in forest monitoring plots (discussed in Section 4.3.2.3) are an alternate data source for recent decades.

Primary production in freshwater lakes has been observed to increase in some Arctic (Michelutti et al., 2005) and boreal lakes, but to decrease in Lake Tanganyika in the tropics (O'Reilly et al., 2003). In both cases the changes were attributed by the authors to climate change.

In summary, there is *high confidence* that net terrestrial ecosystem productivity at the global scale has increased relative to the preindustrial era. There is *low confidence* in attribution of these trends to climate change. Most studies speculate that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, but there is no clear, consistent signal of a climate change contribution (Figure 4-4).

4.3.2.3. Biomass and Carbon Stocks

The forest biomass carbon stock can be estimated from the routine forest monitoring that takes place for management and research purposes. Forest inventories were generally designed to track timber volumes; inferring total biomass and ecosystem carbon stocks requires further information and assumptions, which make absolute values less certain, but have a lesser effect on trend detection. Forest inventory systems are well developed for NH temperate and boreal forest (Nabuurs et al., 2010; Ryan et al., 2010; Wang, B. et al., 2010). Data for tropical and Southern Hemisphere forests and woodlands also exist (Maniatis et al., 2011; Tomppo et al., 2010) but are typically less available and comprehensive (Romijn et al., 2012). More and better data may become available as a result of advances in remote sensing (e.g., Baccini et al., 2012) and increased investment in forest monitoring through initiatives such as the Reduced Emissions from Deforestation and Degradation (REDD) of the United Nations Framework Convention on Climate Change (UNFCCC).

Forests have increased in biomass and carbon stocks over the past half century in Europe (Ciais et al., 2008; Luyssaert et al., 2010) and the USA

(Birdsey et al., 2006). Canadian managed forests increased in biomass only slightly during 1998–2008, because growth was offset by significant losses due to fires and beetle outbreaks (Stinson et al., 2011). Several dozen sites across the moist tropics have been monitored to estimate forest biomass changes. In the Amazon (Phillips et al., 2009) forest biomass has generally increased in recent decades, dropping temporarily after a drought in 2005. Globally, for the period 2000–2007, recently undisturbed forests are estimated to have withdrawn 2.30 ± 0.49 PgC yr^{-1} from the atmosphere, while formerly cleared tropical forests, now regrowing, withdrew an additional 1.72 ± 0.54 PgC yr^{-1} (Pan et al., 2011). The global terrestrial carbon sink is partly offset by the losses of forest carbon stocks to the atmosphere through land use change, largely in the tropics, of 1.1 ± 0.8 PgC yr^{-1} (2000–2009, WGI AR5 Section 6.3.2.6).

The carbon stock in global soils, including litter and peatlands is 1500 to 2400 PgC, with permanently frozen soils adding another 1700 PgC (Davidson and Janssens, 2006). The soil carbon stock is thus more than 10 times greater than the carbon stock in forest biomass (Kindermann et al., 2008). Changes in the size of the soil carbon stock result from changes in the net balance of inputs and losses over a period of many years. Inputs derive from primary production, discussed in Section 4.3.2.2, and are mostly modestly increasing under climate change. Losses result principally through the respiration of soil microbes, which increases with increasing temperature. The present and future temperature sensitivity of microbial respiration remains uncertain (Davidson and Janssens, 2006). An analysis of long-term respiration measurements from the soil around the world suggests that it has increased over the past 2 decades by an amount of 0.1 PgC yr^{-1}, some of which may be due to increased productivity (Bond-Lamberty and Thomson, 2010). If soil respiration were to exceed terrestrial net primary production globally and on a sustained basis, the present net terrestrial sink would become a net source, accelerating the rate of CO_2 build-up in the atmosphere (Luo, 2007).

The carbon stock in freshwater systems is also quite high in global terms. Annual rates of storage (0.03 to 0.07 PgC yr^{-1}) may be trivial compared with sequestration by soils and terrestrial vegetation, but lake sediments are preserved over longer time scales (+10 kyr compared with decades to centuries), and Holocene storage of carbon in lake sediments has been estimated at 820 Pg (Cole et al., 2007). Manmade impoundments represent an increasing and short-lived additional carbon store with conservative annual estimates of 0.16 to 0.2 PgC yr^{-1} (Cole et al., 2007).

A short-duration study of the temperature sensitivity of decomposition in flooded coastal soils, extrapolated to the 21st century, suggested that increases in respiration would exceed increases in future production (Kirwan and Blum, 2011). Further detail on wetland soil carbon stocks can be found in Section 4.3.3.3 on peatlands and on permafrost carbon stocks in Box 4-4 and in Chapter 28.

In summary, biomass and soil carbon stocks in terrestrial ecosystems are currently increasing (*high confidence*) but are vulnerable to loss to the atmosphere as a result of rising temperature, drought, and fire projected in the 21st century (Figure 4-4). Measurements of increased tree growth over the last several decades, a large sink for carbon, are consistent with this but confounding factors such as N deposition, afforestation, and land management make attribution of these trends to climate change difficult (*low confidence*).

4.3.2.4. Evapotranspiration and Water Use Efficiency

Evapotranspiration (ET) includes evaporation from the ground and vegetation surfaces, and transpiration through plant stomata. Both are affected by multiple factors (Luo et al., 2008) including temperature, solar (shortwave) and thermal (longwave) radiation, humidity, soil moisture, and terrestrial water storage; transpiration is additionally affected by CO_2 concentration through its influence on plant stomatal conductance. Studies using lysimeters, evaporation pans, the balance of observed precipitation and runoff, and model reconstructions indicate both increases and decreases in ET in different regions and between approximately 1950 and the present (Huntington, 2008; Teuling et al., 2009; Douville et al., 2013). Flux tower records have at most 15 years duration (FLUXNET, 2012), so there are insufficient data to calculate large-scale, long-term trends. ET can also be estimated from meteorological observations or simulated with models constrained by observations. Estimates of ET from 1120 globally (but non-uniformly) distributed stations indicate that global land mean ET increased by approximately 2.2% between 1982 and 2002, a rate of increase of 0.75 mm yr^{-2} (Wang, K. et al., 2010). Other studies, using data-constrained models, indicated global ET rises of between 0.25 and 1.1 mm yr^{-2} during the 1980s and 1990s (Jung et al., 2010; Vinukollu et al., 2011; Zeng et al., 2012), possibly linked with increased surface solar radiation and thermal radiation (Wild et al., 2008) or warming (Jung et al., 2010). There has been no significant ET trend since approximately 2000 (Jung et al., 2010; Vinukollu et al., 2011; Zeng et al., 2012), possibly due to soil moisture limitation (Jung et al., 2010). Overall, there is *low confidence* in both detection and attribution of long-term trends in ET (Figure 4-4).

Experiments show that rising CO_2 decreases transpiration and increases intrinsic water use efficiency (iWUE, the ratio of photosynthesis to stomatal conductance; Leakey et al., 2009). Some modeling studies suggest that, over the 20th century, the effects of CO_2 on decreasing transpiration are of comparable size but opposite to the effects of rising temperature (Gerten et al., 2008; Peng et al., 2013). However, the observed general increase in ET argues that reduced transpiration cannot be the dominant factor (Huntington, 2008). A meta-analysis of studies at 47 sites across five ecosystem types (Peñuelas et al., 2011) suggests that iWUE for mature trees increased by 20.5% between the 1970s and 2000s. Increased iWUE since preindustrial times (1850 or before) has also been found at several forest sites (Andreu-Hayles et al., 2011; Gagen et al., 2011; Loader et al., 2011; Nock et al., 2011) and also in a temperate semi-natural grassland since 1857 (Koehler et al., 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen et al., 2011).

4.3.2.5. Changes in Species Range, Abundance, and Extinction

Species respond to climate change through genotypic adaptation and phenotypic plasticity; by moving out of unfavorable and into favorable climates; or by going locally or globally extinct (Dawson et al., 2011; Bellard et al., 2012; Peñuelas et al., 2013; see also Section 4.2.3). These responses to climate change can potentially have large impacts on biodiversity and ecosystem services. Genotypic adaptation in the face of strong selection pressure from climate change is typically accompanied

Frequently Asked Questions

FAQ 4.4 | How does climate change contribute to species extinction?

There is a consensus that climate change over the coming century will increase the risk of extinction for many species. When a species becomes extinct, a unique and irreplaceable life form is lost. Even local extinctions can impair the healthy functioning of ecosystems.

Under the fastest rates and largest amounts of projected climate change, many species will be unable to move fast enough to track suitable environments, which will greatly reduce their chances of survival. Under the lowest projected rates and amounts of climate change, and with the assistance of effective conservation actions, the large majority of species will be able to adapt to new climates, or move to places that improve their chances of survival. Loss of habitat and the presence of barriers to species movement increase the risk of extinctions as a result of climate change.

Climate change may have already contributed to the extinction of a small number of species, such as frogs and toads in Central America, but the role of climate change in these recent extinctions is the subject of considerable debate.

by large reductions in abundance (see Section 4.4.1.2). Species range shifts are accompanied by changes in abundance, local extinctions, and colonization that can alter ecosystem services when they affect dominant species such as trees, keystone species such as pollinators, or species that are vectors for diseases (Zarnetske et al., 2012). Global extinctions result in the permanent loss of unique forms of life.

Substantial evidence has accumulated since AR4 reinforcing the conclusion that the geographical ranges of many terrestrial and freshwater plant and animal species have moved over the last several decades in response to warming and that this movement is projected to accelerate over the coming decades under high rates of climate change. Some changes in species abundances appear to be linked to climate change in a predictable manner, with species abundances increasing in areas where climate has become more favorable and vice versa. In contrast, uncertainties concerning attribution to climate change of recent global species extinctions, and in projections of future extinctions, have become more apparent since the AR4.

4.3.2.5.1. Observed species range shifts

The number of studies looking at observed range shifts and the breadth of species examined have greatly increased since AR4. The most important advances since AR4 concern improvements in understanding the relationship between range shifts and changes in climate over the last several decades. The "uphill and poleward" view of species range shifts in response to recent warming (Parmesan and Yohe, 2003; Parmesan, 2006; Fischlin et al., 2007; Chen et al., 2011) is a useful simplification of species responses; however, responses to warming are conditioned by changes in precipitation, land use, species interactions, and many other factors. Investigations of the mechanisms underlying observed range shifts show that climate signals can often be detected, but the impacts of and interactions between changing temperature, precipitation, and land use often result in range shifts that are downhill or away from the poles (Rowe et al., 2010; Crimmins et al., 2011; Hockey et al., 2011; McCain and Colwell, 2011; Rubidge et al., 2011; Pauli et al., 2012; Tingley et al., 2012; Zhu et al., 2012). There are large differences in the ability of species groups (i.e., broad taxonomic categories of species) and species within these groups to track changes in climate through range shifts (Angert et al., 2011; Mattila et al., 2011; Chen et al., 2011). For example, butterflies appear to be able track climate better than birds (community shifts: Devictor et al., 2012; but see Chen et al., 2011 for range shifts) while some plants appear to be lagging far behind climate trends except in mountainous areas (Bertrand et al., 2011; Doxford and Freckleton, 2012; Gottfried et al., 2012; Zhu et al., 2012; Telwala et al., 2013). There is growing evidence that responses at the "trailing edge" of species distributions (i.e., local extinction in areas where climate has become unfavorable) are often less pronounced than responses at the "leading edge" (i.e., colonization of areas where climate has become favorable), which may be related to differences in the rates of local extinction vs. colonization processes (Doak and Morris, 2010; Chen et al., 2011; Brommer et al., 2012; Sunday et al., 2012) and difficulties in detecting local extinction with confidence (Thomas et al., 2006).

Rising water temperatures are also implicated in species range shifts in river fish communities (e.g., Comte and Grenouillet, 2013), combined with a decrease in recruitment and survival as well as range contraction of cold-water species such as salmonids (Bartholow, 2005; Bryant, 2009; Ficke et al., 2007; Jonsson and Jonsson, 2009; Hague et al., 2011). Shifts in freshwater fish species range toward higher elevation and upstream (Hickling et al., 2006; Comte and Grenouillet, 2013) also are not keeping pace with the rate of warming in streams and rivers. While these changes in river temperature regimes may also open up new habitat at higher latitudes (or altitudes) for migratory (Reist et al., 2006) and cool- and warm-water species of fish (Tisseuil et al., 2012), there is *high confidence* that range contraction threatens the long-term persistence of some fully aquatic species.

Rates of recent climate change have varied greatly across the globe, ranging from rapid warming to cooling (Burrows et al., 2011; Dobrowski et al., 2013). Taking this spatial variation into account should enhance the ability to detect climate-related range shifts. A recent synthesis of range shifts indicates that terrestrial animal species have moved at rates that correspond better with changes in temperature when climate is measured only in the regions where the range shifts were observed

(Chen et al., 2011), providing greater confidence in attribution of the range shifts to climate change. Average range shifts across taxa and regions in this study were approximately 17 km poleward and 11 m up in altitude per decade, velocities that are two to three times greater than previous estimates (compare with Parmesan and Yohe, 2003; Fischlin et al., 2007), but these responses differ greatly among species groups. However, this approach remains a simplification, as the climate drivers of species range changes, for example, temperature and precipitation, have frequently shifted in different geographical directions (Dobrowski et al., 2013). Disentangling these conflicting climate signals can help explain complex responses of species ranges to changes in climate (Tingley et al., 2012). Overall, studies since AR4 show that species range changes result from interactions among climate drivers and between climate and non-climate factors. It is the greater understanding of these interactions, combined with increased geographical scope, that leads to *high confidence* that several well-studied species groups, such as insects and birds, have shifted their ranges over significant distances (tens of kilometers or more) over the last several decades, and that these range shifts can be attributed to changes in climate. But for many other species groups range shifts are more difficult to attribute to changes in climate because the climate signal is small, there are many confounding factors, differences between expected and observed range shifts are large, or variability within or between studies is high. Thus there is only *medium confidence* in detection and attribution when examined across all species and all regions.

4.3.2.5.2. Future range shifts

Projections of climate change impacts on future species range shifts since the AR4 have been dominated by studies using Ecological Niche Models (ENMs) that project future ranges based on correlative models of current relationships between environmental factors and species distribution (Peterson et al., 2011). A variety of process-based models are starting to be more widely used to make projections of future species distributions (Buckley et al., 2010; Beale and Lennon, 2012; Cheaib et al., 2012; Higgins et al., 2012; Foden et al., 2013). Model comparisons show that correlative models generally predict larger range shifts than process-based models for trees (Morin and Thuiller, 2009; Kearney et al., 2010; Cheaib et al., 2012). For other species groups that have been studied, differences in projections between model types show no clear tendency (Kearney et al., 2009; Buckley et al., 2010; Bateman et al., 2012). There has been some progress in model validation: projected species shifts are broadly coherent with species responses to climate change in the paleontological record and with observed recent species shifts (see Section 4.2.2 and above in this section), but further validation is needed (Green et al., 2008; Pearman et al., 2008; Nogues-Bravo et al., 2010; Dawson et al., 2011). Modeling studies typically do not account for a number of key mechanisms mediating range shifts, such as genetic adaptation and phenotypic plasticity (see Section 4.4.1.2), species interactions, or human-mediated effects. An important limitation in most studies is that realistic species displacement rates are not accounted for (i.e., rates at which species are able to shift their ranges through dispersal and establishment); as such, they only indicate changes in the location of favorable and unfavorable climates, from which potential shifts in species distribution can be inferred, but not rates of change (Bateman et al., 2013).

Analyses and models developed since AR4 permit the estimation of the ability of a wide range of species to track climate change. Figure 4-5 provides a synthesis of the projected abilities of several species groups to track climate change. This analysis is based on (1) past and future climate velocity, which is a measure of the rate of climate displacement across a landscape and provides an indication of the speed at which an organism would need to move in order to keep pace with the changing climatic conditions (Loarie et al., 2009; Burrows et al., 2011; Chen et al., 2011; Sandel et al., 2011; Feeley and Rehm, 2012; Dobrowski et al., 2013); and (2) species displacement rates across landscapes for a broad range of species (e.g., Stevens, V.M. et al., 2010; Nathan et al., 2011; Barbet-Massin et al., 2012; Kappes and Haase, 2012; Meier et al., 2012; Schloss et al., 2012; see additional references in Figure 4-5 legend). Comparisons of these rates indicate whether species are projected to be able to track climate as it changes. When species displacement capacity exceeds climate velocity it is inferred that species will be able to keep pace with climate change; when displacement capacity is lower than projected climate velocities then they will not, within the bounds of uncertainty of both parameters. This simplified analysis is coherent with more sophisticated model analyses of climate-induced species displacement across landscapes, some of which have evaluated additional constraints such as demographics, habitat fragmentation, or competition (e.g., Meier et al., 2012; Schloss et al., 2012).

Rates of climate change over the 20th century and projected for the 21st century are shown in Figure 4-5a. Rates of climate change for global land surfaces are given for IPCC AR5 climate projections under a wide range of GHG emissions scenarios (i.e., WGI AR5 Chapter 12; Knutti and Sedláček, 2012). Rates of global warming for land surfaces have averaged approximately 0.03°C yr^{-1} since 1980, but have slowed over the last decade and a half (WGI AR5 Chapter 2). At the low end of projected future rates of warming, rates decrease over time, reaching near zero by the end of the century (RCP2.6). At the high end, projected rates increase over time, exceeding 0.06°C yr^{-1} by the end of the century (RCP8.5), and perhaps above 0.08°C yr^{-1} at the upper bound.

Climate velocity is defined as the rate of change in climate over time (e.g., °C yr^{-1}, if only temperature is considered) divided by the rate of change in climate over distance (e.g., °C km^{-1}, if only temperature is considered) and therefore depends on regional rates of climate change and the degree of altitudinal relief (Figure 4-5b; Loarie et al., 2009; Dobrowski et al., 2013). For example, climate velocity for temperature is low in mountainous areas because the change in temperature over short distances is large (e.g., Rocky Mountains, Andes, Alps, Himalayas; Figure 4-5b, leftmost axis). Climate velocity for temperature is generally high in flat areas because the rate of change in temperature over distance is low (e.g., parts of the USA Midwest, Amazon basin, West Africa, central Australia; Figure 4-5b, rightmost axis). In flat areas, climate velocity can exceed 8 km yr^{-1} for the highest rates of projected climate change (RCP8.5). We have focused on climate velocity for temperature change, but several analyses also account for precipitation change.

Rates of displacement vary greatly within and among species groups (Figure 4-5c). Some species groups, notably herbaceous plants and trees, generally have very low displacement capacity. Other species groups such as butterflies, birds (not shown), and large vertebrates generally have a very high capacity to disperse across landscapes, nonetheless

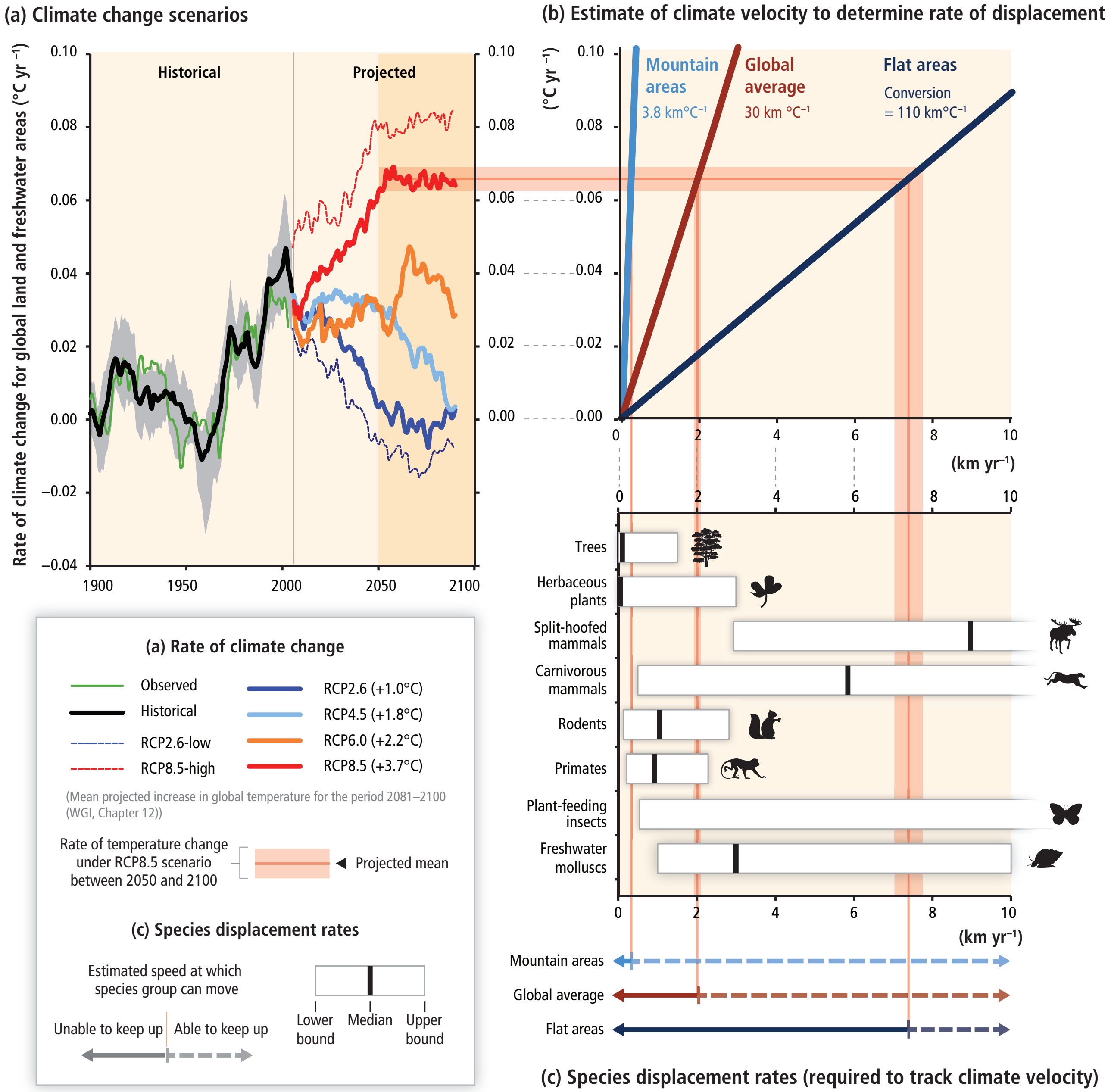

Figure 4-5 | (a) Rates of climate change, (b) corresponding climate velocities, and (c) rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention. Horizontal and vertical pink bands illustrate the interpretation of this figure. Climate velocities for a given range of rates of climate change are determined by tracing a band from the range of rates in (a) to the points of intersection with the three climate velocity scalars in (b). Comparisons with species displacement rates are made by tracing vertical bands from the points of intersection on the climate velocity scalars down to the species displacement rates in (c). Species groups with displacement rates below the band are projected to be unable to track climate in the absence of human intervention. (a) Observed rates of climate change for global land areas are derived from Climatic Research Unit/Hadley Centre gridded land-surface air temperature version 4 (CRUTEM4) climate data reanalysis; all other rates are calculated based on the average of Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model ensembles for the historical period (gray shading indicates model uncertainty) and for the future based on the four Representative Concentration Pathway (RCP) emissions scenarios. Data were smoothed using a 20-year sliding window, and rates are means of between 17 and 30 models using one member per model. Global average temperatures at the end of the 21st century for the four RCP scenarios are from WGI AR5 Chapter 12. (b) Estimates of climate velocity for temperature were synthesized from historical and projected future relationships between rates of temperature change and climate velocity (historical: Burrows et al., 2011; Chen et al., 2011; Dobrowski et al., 2013; projected future: Loarie et al., 2009; Sandel et al., 2011; Feeley and Rehm, 2012). The three scalars are climate velocities that are representative of mountainous areas (left), averaged across global land areas (center), and large flat regions (right). (c) Rates of displacement are given with an estimate of the median (black bars) and range (boxes = approximately 95% of observations or models for herbaceous plants, trees, and plant-feeding insects or median ± 1.5 inter-quartile range for mammals). Displacement rates for herbaceous plants were derived from paleobotanical records, modern plant invasion rates, and genetic analyses (Kinlan and Gaines, 2003). Displacement estimates for trees are based on reconstructed rates of tree migration during the Holocene (Clark, 1998; Clark et al., 2003; Kinlan and Gaines, 2003; McLachlan et al., 2005; Nathan, 2006; Pearson, 2006) and modeled tree dispersal and establishment in response to future climate change (Higgins et al., 2003; Iverson et al., 2004; Epstein et al., 2007; Goetz et al., 2011; Nathan et al., 2011; Meier et al., 2012; Sato and Ise, 2012). Displacement rates for mammals were based on modeled dispersal rates of a wide range of mammal species (mean of Schloss et al., 2012 for Western Hemisphere mammals and rates calculated from global assessments of dispersal distance by Santini et al., 2013 and generation length by Pacifici et al., 2013). Displacement rates for phytophagous insects are based on observed dispersal distances and genetic analyses (Peterson and Denno, 1998; Kinlan and Gaines, 2003; Schneider, 2003; Berg et al., 2010; Chen et al., 2011). The estimate of median displacement rate for this group exceeds the highest rates on the axis. These displacement rates do not take into account limitations imposed by host plants. Displacement estimates for freshwater molluscs correspond to the range of passive plus active dispersal rates for upstream movement (Kappes and Haase, 2012).

some species in these groups have low dispersal capacity. Current and future rates of climate change correspond to climate velocities that exceed rates of displacement for several species groups for most climate change scenarios. This is particularly true for mid- and late-successional trees that have maximum displacement rates that are on the order of tens to a few hundreds of meters per year. Overall, many plant species are foreseen to be able to track climates only in mountainous areas at medium to high rates of warming, though there is uncertainty concerning the potential role of long-distance dispersal (Pearson, 2006). Primates generally have substantially higher dispersal capacity than trees; however, a large fraction of primates are found in regions with very high climate velocities, in particular the Amazon basin, thereby putting them at high risk of being unable to track climates even at relatively low rates of climate change (Schloss et al., 2012). On a global average, many rodents, as well as some carnivores and freshwater molluscs, are projected to be unable to track climate at very high rates of climate change (i.e., >0.06°C yr^{-1}). These projected differences in species ability to keep pace with future climate change are broadly coherent with observations of species ability or inability to track recent global warming (see Section 4.3.2.5.1).

Humans can increase species displacement rates by intentionally or unintentionally dispersing individuals or propagules. For example, many economically important tree species may be deliberately moved on large scales as part of climate adaptation strategies in forestry in some regions (Lindner et al., 2010). Human activities can also substantially reduce displacement rates. In particular, habitat loss and fragmentation typically reduces displacement rates, sometimes substantially (Eycott et al., 2012; Hodgson et al., 2012; Meier et al., 2012; Schloss et al., 2012). The degree to which habitat fragmentation slows displacement depends on many factors, including the spatial pattern of the fragments and corridors, maximum dispersal distances, population dynamics, and the suitability of intervening modified habitats as stepping-stones (Pearson and Dawson, 2003). Species and habitat dependencies may also speed or hinder species displacement. For example, host plants are projected to move much more slowly than most herbivorous insects, substantially slowing displacement of the insects if they are unable to switch host plants (Schweiger et al., 2012). Likewise, many habitats are structured by slow moving plants, so habitat shifts are projected to lag behind climate change (Hickler et al., 2012; Jones et al., 2012), which will in turn mediate the movements of habitat specialists.

There are significant uncertainties in climate velocities, measured estimates of dispersal and establishment rates, and model formulations. Climate velocities are calculated using a variety of methods and spatial resolutions, making direct comparisons difficult and leading to *low confidence* in estimates of climate velocities in Figure 4-5b (*limited evidence* and *medium agreement*). The lowest estimates of global average climate velocity (Figure 4-5b, center axis) are about half the best estimate values we show on the climate velocity axes (Loarie et al., 2009), while the highest estimates are about four times higher (Burrows et al., 2011), but high estimates may be artefacts of using very large spatial resolutions (Dobrowski et al., 2013). In addition, the climate velocities used in Figure 4-5 are based on temperature alone, and recent analyses indicate that including more climate factors increases climate velocity (Feeley and Rehm, 2012; Dobrowski et al., 2013). Species displacement rates are calculated based on a very wide range of methods including rates of displacement in the paleontological record, rates of current range shifts due to climate warming, models of dispersal and establishment, maximum observed dispersal distances and genetic analyses (e.g., Kinlan and Gaines, 2003; Stevens, V.M. et al., 2010). There are often large differences in estimates of dispersal rates across methods due to intrinsic uncertainties in the methods and differences in the mechanisms included (Kinlan and Gaines, 2003; Stevens, V.M. et al., 2010). For example, estimates of tree displacement rates are frequently based on models or observations that explicitly or implicitly include both dispersal of seeds and biotic and abiotic factors controlling establishment of adult trees. Displacement rates of trees are often more strongly limited by establishment than dispersal (Higgins et al., 2003; Meier et al., 2012). It is reasonable to expect that limits on establishment could also be important for other species groups, but often only dispersal rates have been calculated, leading to an overestimation of displacement rates. For trees there is *medium confidence* in projections of their displacement rates due to the large number of studies of past, current, and future displacement rates (*robust evidence* and *medium agreement*). Less is known for other broad species groups such as mammals, so there is only *low confidence* in estimates of their displacement capacity. Estimates for other groups, such as freshwater molluscs, are based on very little data, so estimates of their dispersal capacity are poorly constrained.

Despite large uncertainties in displacement capacity and climate velocity, the rates of displacement required to track the highest rates of climate change (RCP8.5) are so high that many species will be unable to do so (*high confidence*). Moderate rates of projected climate change (RCP4.5 and RCP6.0) would allow more species to track climate, but would still exceed the capacity of many species to track climate (*medium confidence*). The lowest rates of projected climate change (RCP2.6) would allow most species to track climate toward the end of the century (*high confidence*). This analysis highlights the importance of rates of climate change as an important component of climate change impacts on species and ecosystems. For example, differences in the magnitude of climate change between scenarios are small at mid-21st century (WGI AR5 Chapter 12), but the differences in rates of climate change are large. At mid-century, it is projected that species would need to move little at the lowest rates of climate change (RCP2.6), but will need to move approximately 70 km per decade in flat areas in order to track climate at the highest rates of climate change (RCP8.5).

Species that cannot move fast enough to keep pace with the rate of climate change will lose favorable climate space and experience large range contractions (Warren et al., 2013), whereas displacement that keeps pace with climate change greatly increases the fraction of species that can maintain or increase their range size (Menéndez et al., 2008; Pateman et al., 2012). Mountains provide an extremely important climate refuge for many species because the rate of displacement required to track climate is low (Figure 4-5b; Colwell et al., 2008; Engler et al., 2011; Gottfried et al., 2012; Pauli et al., 2012; but see Dullinger et al., 2012). However, species that already occur near mountaintops (or other boundaries) are among the most threatened by climate change because they cannot move upwards (Ponniah and Hughes, 2004; Thuiller et al., 2005; Raxworthy et al., 2008; Engler et al., 2011; Sauer et al., 2011). The consequences of losing favorable climate space are not yet well understood. The extent to which adaptive responses might allow persistence in areas of unfavorable climates is discussed in Section

4.4.1.2. In the absence of adaptation, losing favorable climate space is projected to lead to reduced fitness, declining abundance, and local extinction, with potentially large effects on biodiversity and ecosystem services (see evidence of early signs of this for trees in Box 4-2).

4.3.2.5.3. Observed changes in abundance and local extinctions

Observations of range shifts imply changes in abundance, that is, colonization at the "leading edge" and local extinction at the "trailing edge" of ranges. Evidence that the attribution of these responses to recent changes in climate can be made with *high confidence* for several species groups is reviewed here (Section 4.3.2.5), in AR4, and by Cahill et al. (2013). Changes in abundance, as measured by changes in the population size of individual species or shifts in community structure within existing range limits, have also occurred in response to recent global warming (*high confidence*; Thaxter et al., 2010; Bertrand et al., 2011; Naito and Cairns, 2011; Rubidge et al., 2011; Devictor et al., 2012; Tingley et al., 2012; Vadadi-Fulop et al., 2012; Cahill et al., 2013; Ruiz-Labourdette et al., 2013). Confident attribution to recent global warming is hindered by confounding factors such as disease, land use change, and invasive species (Cahill et al., 2013). New tentative conclusions since AR4 are that climate-related changes in abundance and local extinctions appear to be more strongly related to species interactions than to physiological tolerance limits (*low confidence*; Cahill et al., 2013) and that precipitation can be a stronger driver of abundance change than temperature in many cases (Tian et al., 2011; Tingley et al., 2012). This gives weight to concerns that biological interactions, which are poorly known and modeled, may play a critical role in mediating the impacts of future climate change on species abundance and local extinctions (Dunn et al., 2009; Bellard et al., 2012; Hannah, 2012; Urban et al., 2012; Vadadi-Fulop et al., 2012).

A few examples illustrate the types of change in abundance that are being observed and the challenges in attributing these to recent global warming. Some of the clearest examples of climate-related changes in species populations come from high-latitude ecosystems where non-climate drivers are of lesser importance. For example, both satellite data and a large number of long-term observations indicate that shrub abundance is generally increasing over broad areas of Arctic tundra, which is coherent with predicted shifts in community structure due to warming (Epstein et al., 2007; Goetz et al., 2011; Myers-Smith et al., 2011). In the Antarctic, two native vascular plants, Antarctic pearlwort (*Colobanthus quitensis*) and Antarctic hair grass (*Deschampsia antarctica*), have become more prolific over recent decades, perhaps because they benefit more from warming of soils than do mosses (Hill et al., 2011). Penguin populations have declined in several areas of the Antarctic, including a recent local extinction of an Emperor penguin (*Aptenodytes forsteri*) population that has been attributed to regional changes in climate (Trathan et al., 2011). The attribution of these declines to changes in regional climate is well supported, but the link to global warming is tenuous (Barbraud et al., 2011).

Mountains also provide good examples of changes in abundance that can be linked to climate because very strong climate gradients are found there. AR4 highlighted these responses, and the case for changes in abundance, in particular plants, has become stronger since then. For example, Pauli et al. (2012) reported an increase in species richness from plant communities of mountaintops in the European boreal and temperate zones due to increasing temperatures and a decrease in species richness on the Mediterranean mountain tops, probably due to a decrease in the water availability in southern Europe. An increase in the population size of warm-adapted species at high altitudes also appears to be attributable to increasing temperatures (Gottfried et al., 2012). However, these attributions are complicated by other anthropogenic influences such as changes in grazing pressure, atmospheric N deposition, and forest management practices (Gottfried et al., 2012). Altitudinal gradients in local and global extinctions of amphibians also contributed to the attribution of these extinctions to recent global warming, although this attribution remains controversial (see Section 4.3.2.5.5).

4.3.2.5.4. Projected changes in abundance and local extinction

Ecological niche models do not predict population changes, but the shifts in suitable climates can be used to infer areas where species populations might decline or increase. These models project that local extinction risk by the end of the 21st century due to climate change will vary widely, ranging from almost no increase in local extinction risk within the current range for some species or species groups to greatly increased risk of local extinctions in more than 95% of the present-day range for others (Settele et al., 2008; Bellard et al., 2012). Projected local colonization rates are equally variable. There has been progress in coupling species distribution models and species abundance models for a wide range of organisms (Keith et al., 2008; Midgley et al., 2010; Matthews et al., 2011; Schippers et al., 2011; Oliver et al., 2012a; Renwick et al., 2012). These hybrid approaches predict extinction risk directly, rather than by inference from changes in climate suitability (Fordham et al., 2012). The main conclusions from these studies are that changes in species abundance and local extinction risk as a result of climate change can range from highly positive to highly negative, and are determined by a combination of factors, including its environmental niche, demographics, and life history traits, as well as interactions among these factors (Aiello-Lammens et al., 2011; Clavero et al., 2011; Conlisk et al., 2012; Fordham et al., 2012; Swab et al., 2012).

Changes in abundances will also be accompanied by changes in genetic diversity (see also Section 4.4.1.2). At the intraspecific level, future climate change is projected to induce losses of genetic diversity when it results in range contraction (Balint et al., 2011; Pauls et al., 2013). In addition, there is theoretical and observational evidence this loss of genetic diversity will depend on rates of migration and range contraction (Arenas et al., 2012). In these cases, reductions in genetic diversity may then decrease the ability of species to adapt to further climate change or other global changes. Climate change may also compound losses of genetic diversity that are already occurring due to other global changes such as the introduction of alien species or habitat fragmentation (Winter et al., 2009; see also Section 4.2.4.6).

4.3.2.5.5. Observed global extinctions

Global species extinctions, many of them caused by human activities, are now occurring at rates that approach or exceed the upper limits of observed natural rates of extinction in the fossil record (Barnosky et al., 2011). However, across all taxa there is only *low confidence* that rates of species extinctions have increased over the last several decades (birds: Szabo et al., 2012; but see Kiesecker, 2011, for amphibians). Most extinctions over the last several centuries have been attributed to habitat loss, overexploitation, pollution, or invasive species, and these are the most important current drivers of extinctions (Millennium Ecosystem Assessment, 2005b; Hofmann and Todgham, 2010; Cahill et al., 2013). Of the more than 800 global extinctions documented by the International Union for Conservation of Nature (IUCN), only 20 have been tenuously linked to recent climate change (Cahill et al., 2013; see also Hoffmann et al., 2010; Szabo et al., 2012). Molluscs, especially freshwater molluscs, have by far the highest rate of documented extinctions of all species groups (Barnosky et al., 2011). Mollusc extinctions are attributed primarily to invasive species, habitat modification, and pollution; changes in climate are rarely evoked as a driver (Lydeard et al., 2004; Regnier et al., 2009; Chiba and Roy, 2011; but see a few cases in Kappes and Haase, 2012; Cahill et al., 2013). Freshwater fish have the highest documented extinction rates of all vertebrates, and again very few have been attributed to changing climate, even tenuously (Burkhead, 2012; Cahill et al., 2013). In contrast, changes in climate have been identified as one of the key drivers of extinctions of amphibians (Pounds et al., 2006). There have been more than 160 probable extinctions of amphibians documented over the last 2 decades, many of them in Central America (Pounds et al., 2006; Kiesecker, 2011). The most notable cases have been the golden toad (*Bufo periglenes*) and Monteverde harlequin frog (*Atelopus varius*) of Central America, which belong to a group of amphibians with high rates of extinction previously ascribed to global warming with "very high confidence" (Pounds et al., 2006; Fischlin et al., 2007). This case has raised a number of important issues about attribution because (1) the proximate causes of extinction of these and other Central American frogs appear to be an extremely virulent invasive fungal infection and land use change, with regional changes in climate as a potential contributing factor, and (2) changes in regional climate may have been related to natural climate fluctuations rather than anthropogenic climate change (Sodhi et al., 2008; Lips et al., 2008; Anchukaitis and Evans, 2010; Bustamante et al., 2010; Collins, 2010; Vredenburg et al., 2010; Kiesecker, 2011; McKenzie and Peterson, 2012; McMenamin and Hannah, 2012). Owing to *low agreement* among studies there is only *medium confidence* in detection of extinctions and attribution of Central American amphibian extinctions to climate change. While this case highlights difficulties in attribution of extinctions to recent global warming, it also points to a growing consensus that it is the interaction of climate change with other global change pressures that poses the greatest threat to species (Brook et al., 2008; Pereira et al., 2010; Hof et al., 2011b). Overall, there is *very low confidence* that observed species extinctions can be attributed to recent climate warming, owing to the very low fraction of global extinctions that have been ascribed to climate change and tenuous nature of most attributions.

4.3.2.5.6 Projected future species extinctions

Projections of future extinctions due to climate change have received considerable attention since AR4. AR4 stated with *medium confidence* "that approximately 20–30% of the plant and animal species assessed to date are at increasing risk of extinction as global mean temperatures exceed a warming of 2-3°C above preindustrial levels" (Fischlin et al., 2007). All model-based analyses since AR4 broadly confirm this concern, leading to *high confidence* that climate change will contribute to increased extinction risk for terrestrial and freshwater species over the coming century (Pereira et al., 2010; Sinervo et al., 2010; Pearson, 2011; Warren et al., 2011, 2012; Bellard et al., 2012; Hannah, 2012; Ihlow et al., 2012; Sekercioglu et al., 2012; Wearn et al., 2012; Foden et al., 2013). Most studies indicate that extinction risk rises rapidly with increasing levels of climate change, but some do not (Pereira et al., 2010). The limited number of studies that have directly compared land use and climate change drivers have concluded that projected land use change will continue to be a more important driver of extinction risk throughout the 21st century (Pereira et al., 2010). There is, however, broad agreement that land use, and habitat fragmentation in particular, will pose serious impediments to species adaptation to climate change as it is projected to reduce the capacity of many species to track climate (see Section 4.3.2.5.3). These considerations lead to the assessment that future species extinctions are a high risk because the consequences of climate change are potentially severe, widespread, and irreversible, as extinctions constitute the permanent loss of unique life forms.

There is, however, low agreement concerning the overall fraction of species at risk, the taxa and places most at risk, and the time scale for climate change-driven extinctions to occur. Part of this uncertainty arises from differences in extinction risks within and between modeling studies: this uncertainty has been evaluated in AR4 and subsequent syntheses (Pereira et al., 2010; Warren et al., 2011; Bellard et al., 2012; Cameron, 2012). All studies project increased extinction risk by the end of the 21st century due to climate change, but as indicated in AR4 the range of estimates is large. Recent syntheses indicate that model-based estimates of the fraction of species at substantially increased risk of extinction due to 21st century climate change range from below 1% to above 50% of species in the groups that have been studied (Pereira et al., 2010; Bellard et al., 2012; Cameron, 2012; Foden et al., 2013). Differences in modeling methods, species groups, and climate scenarios between studies make comparisons between estimates difficult (Pereira et al., 2010; Warren et al., 2011; Cameron, 2012).

Many papers published since AR4 argue that the uncertainty may be even higher than indicated in syntheses of model projections, due to limitations in the ability of current models to evaluate extinction risk (e.g., Kuussaari et al., 2009; Pereira et al., 2010; Dawson et al., 2011; McMahon et al., 2011; Pearson, 2011; Araujo and Peterson, 2012; Bellard et al., 2012; Fordham et al., 2012; Hannah, 2012; Kramer et al., 2012; Zurell et al., 2012; Halley et al., 2013; Moritz and Agudo, 2013). Models frequently do not account for genetic and phenotypic adaptive capacity, dispersal capacity, population dynamics, the effects of habitat fragmentation and loss, community interactions, micro-refugia, and the effects of rising CO_2 concentrations, all of which could play a major role in determining species vulnerability to climate change, causing models to either over- or underestimate risk. In addition, difficulties in model validation, large variation in the climate sensitivity of species groups, and uncertainties about time scales linking extinction risks to range reductions also lead to large uncertainty in model-based estimates of extinction risk.

A variety of studies since AR4 illustrate how accounting for these factors alters estimates of extinction risk. Accounting for biotic interactions such as pollination or predator-prey networks can increase modeled extinction risks, at least for certain areas and species groups (Schweiger et al., 2008; Urban et al., 2008; Hannah, 2012; Nakazawa and Doi, 2012), or can decrease extinction risk (Menéndez et al., 2008; Pateman et al., 2012). Accounting for climatic variation at fine spatial scales may increase (Randin et al., 2009; Gillingham et al., 2012; Suggitt et al., 2012; Dobrowski et al., 2013; Franklin et al., 2013) or decrease (Trivedi et al., 2008; Engler et al., 2011; Shimazaki et al., 2012) the persistence of small populations under future climate change. Several recent studies indicate that correlative species distribution models (the type of model most frequently used for evaluating species extinction risk) tend to be much more pessimistic concerning plant species range contractions and the inferred extinction risks due to climate change when compared to mechanistic models that explicitly account for the interactions between climate change and protective effects of rising CO_2 concentrations on plants (Morin and Thuiller, 2009; Kearney et al., 2010; Cheaib et al., 2012). Models that account for population dynamics indicate that some species populations, such as those of polar bears (Hunter et al., 2010), will decline precipitously over the course of the next century due to climate change, greatly increasing extinction risk, while others may not (Keith et al., 2008). Phenotypic plasticity in one very well-studied temperate bird population has been estimated to be sufficient to keep extinction risk low even with projected warming exceeding 2–3°C (Vedder et al., 2013), but this and other studies suggest that capacity for adaptation is often substantially lower in species with long generation times (see Section 4.4.1.2). There is evidence that interactions between physiological tolerances and regional climate change will lead to large taxonomic and spatial variation in extinction risk (Deutsch et al., 2008; Sinervo et al., 2010). Even species whose populations are not projected to decline rapidly over the next century can face a substantial "extinction debt," that is, will be in unfavorable climates that over a period of many centuries are projected to lead to large reductions in population size and increase the risk of extinction (Dullinger et al., 2012). Finally, evidence from the paleontological record indicating very low extinction rates over the last several hundred thousand years of substantial natural fluctuations in climate—with a few notable exceptions such as large land animal extinctions during the Holocene—has led to concern that forecasts of very high extinction rates due entirely to climate change may be overestimated (Botkin et al., 2007; Dawson et al., 2011; Hof et al., 2011a; Willis and MacDonald, 2011; Moritz and Agudo, 2013). However, as indicated in Section 4.2.3, no past climate changes are precise analogs of future climate change in terms of speed, magnitude, and spatial scale; nor did they occur alongside the habitat modification, overexploitation, pollution, and invasive species that are characteristic of the 21st century. Therefore the paleontological record cannot easily be used to assess future extinction risk due to climate change.

4.3.3. Impacts on and Risks for Major Systems

This section covers impacts of climate change on broad categories of terrestrial and freshwater ecosystems of the world. We have placed a particular emphasis on those ecosystems that have high exposure to climate change or that may be pushed past thresholds or "tipping points" by climate change. Two geographical regions of particularly high risk have been identified in recent studies: (1) tropics, due to the limited capacity of species to adapt to moderate global warming and (2) high northern latitude systems, because temperature increases are projected to be large. There has been a tendency to oppose these two points of view, but there is a high risk in both types of systems, albeit for different reasons (Corlett, 2011). Tropical species, which experienced low inter- and intra-annual climate variability, have evolved within narrow thermal limits, and are already near their upper thermal limits (ectotherms: Deutsch et al., 2008; Huey et al., 2012; birds: Sekercioglu et al., 2012; trees: Corlett, 2011). On this basis, tropical species and ecosystems are predicted to be more sensitive to climate change than species and ecosystems that have evolutionary histories of climatic variability (e.g., Arctic and boreal ecosystems; Beaumont et al., 2011). However, there are physiological, evolutionary, and ecological arguments that tropical species and ecosystem sensitivities to climate change are complex and may not be particularly high compared to other systems (Gonzalez et al., 2010; Corlett, 2011; Laurance et al., 2011; Gunderson and Leal, 2012; Walters et al., 2012). High-latitude systems have the greatest projected exposure to rising temperatures (WGI AR5 Chapter 12; Diffenbaugh and Giorgi, 2012), which all else being equal would put them at higher risk. The greatest degree of recent climate warming has occurred at high northern latitudes (Burrows et al., 2011) and the strongest and clearest signals of recent climate warming impacts on ecosystems come from these regions. A comparison of modeled biome level vulnerability indicated that temperate and high northern latitude systems are also the most vulnerable in the future (Gonzalez et al., 2010).

Several potential tipping points (see Section 4.2.1) with regional and global consequences have been identified (Scheffer, 2009); two are elaborated in Boxes 4-3 (Amazon dieback) and 4-4 (tundra-boreal regime shift). An assessment by the authors of this chapter of the top risks in relation to climate change and terrestrial and freshwater ecosystems is presented in Table 4-3.

4.3.3.1. Forests and Woodlands

Forests and woodlands are principal providers of timber, pulp, bioenergy, water, food, medicines, and recreation opportunities and can play prominent roles in cultural traditions. Forests are the habitat of a large fraction of the Earth's terrestrial plant and animal species, with the highest concentrations and levels of endemism found in tropical regions (Gibson et al., 2011). Climate change and forests interact strongly; air temperature, solar radiation, rainfall, and atmospheric CO_2 concentrations are major drivers of forest productivity and forest dynamics, and forests help control climate through the large amounts of carbon they can remove from the atmosphere or release, through absorption or reflection of solar radiation (albedo), cooling through evapotranspiration, and the production of cloud-forming aerosols (Arneth et al., 2010; Pan et al., 2011; Pielke et al., 2011).

Combinations of ground-based observations, atmospheric carbon budgets, and satellite measurements indicate with *high confidence* that forests are currently a net sink for carbon at the global scale. It is estimated that intact and regrowing forests currently contain 860 ± 70 PgC and sequestered 4.0 ± 0.7 PgC yr^{-1} globally between 2000 and 2007 (WGI AR5 Chapter 6; Canadell et al., 2007; Pan et al., 2011; Le Quéré et al., 2012). The carbon taken up by intact and regrowing forests was counterbalanced by a release due to land use change of 2.8 ± 0.4

4

Table 4-3 | Key risks for terrestrial and freshwater ecosystems from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near term (here, assessed over 2030–2040), and longer term (here, assessed over 2080–2100). For the near term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer term era of climate options, risk levels are presented for global mean temperature increase of 2°C and 4°C above pre-industrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by icons. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions.

Climate-related drivers of impacts				Level of risk & potential for adaptation
Warming trend	Extreme temperature	Drying trend	Precipitation	Potential for additional adaptation to reduce risk; Risk level with **high** adaptation; Risk level with **current** adaptation

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation (Very low – Medium – Very high)
Reduction in terrestrial carbon sink: Carbon stored in terrestrial ecosystems is vulnerable to loss back into the atmosphere. Key mechanisms include an increase in fire frequency due to climate change and the sensitivity of ecosystem respiration to rising temperatures. (*medium confidence*) [4.2.4, 4.3.2, 4.3.3]	Adaptation prospects include managing land use (including deforestation), fire, and other disturbances and non-climatic stressors.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	
Boreal tipping point: Arctic ecosystems are vulnerable to abrupt change related to the thawing of permafrost and spread of shrubs in tundra and increase in pests and fires in boreal forests. (*medium confidence*) [4.3.3.1.1, Box 4-4]	There are few adaptation options in the Arctic.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	
Amazon tipping point: Moist Amazon forests could change abruptly to less carbon-dense drought and fire-adapted ecosystems. (*low confidence*) [4.3.3.1.3, Box 4-3]	Policy and market measures to reduce deforestation and fire.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	
Tree mortality and forest loss: Tree mortality has been observed to have increased in many places and has been attributed in some cases to direct climate effects and indirect effects due to pests and diseases. The dead trees increase the risk of forest fires. (*medium confidence*) [4.3.3.1, Box 4-2]	Adaption options include more effective management of fire, pests, and pathogens.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	
Increased risk of species extinction: A large fraction of the species that have been assessed are vulnerable to extinction as a result of climate change, often in interaction with other threats. Species with an intrinsically low dispersal rate, especially when occupying flat landscapes where the projected climate velocity is high, and species in isolated habitats such as mountain tops, islands, or small protected areas are especially at risk. Cascading effects through organism interactions, and especially those vulnerable to timing (phenological) changes, amplify the risk. (*high confidence*) [4.3.2.5, 4.3.3.3, 4.3.2.1, 4.4.2]	Adaptation options include reducing habitat modification, habitat fragmentation, pollution, over-exploitation, and invasive species; protected area expansion, assisted dispersal, *ex situ* conservation.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	
Invasion by non-native species: Disruptions of species interactions and the increase in physiological stress as a result of being near the edge or outside of the historical climate niche increases the vulnerability of ecosystems to invasion by non-native (alien) species, especially in the presence of increased long-distance dispersal opportunities. In the extreme this can result in biome shifts, with consequent changes in the spectrum of ecosystem services provided. (*high confidence*) [4.2.4.6]	Climate is one driver among many. Adaptation options are limited, largely based on reducing other stresses and measures to slow the unintended arrival of aliens. Intensive direct intervention in controlling emergent invasive species is an option, but could be overwhelmed by the rapidly rising number of cases.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	

PgC yr^{-1} over this same period due mostly to tropical deforestation and forest degradation associated with logging and fire, resulting in a net carbon balance for global forests of 1.1±0.8 PgC yr^{-1}.

The future of the interaction between climate and forests is unclear. The carbon taken up by intact and regrowing forests appears to have stabilized compared to the 1990s, after having increased in the 1970s and 1980s (Canadell et al., 2007; Pan et al., 2011). There is *medium confidence* that the terrestrial carbon sink is weakening. The drivers behind the forest carbon sink vary greatly across regions. They include forest regrowth and stimulation of carbon sequestration by climate change, rising atmospheric CO_2 concentrations, and nitrogen deposition

(Pan et al., 2011; see also Sections 4.2.4.1, 4.2.4.2, 4.2.4.4). Most models suggest that rising temperatures, drought, and fires will lead to forests becoming a weaker sink or a net carbon source before the end of the century (Sitch et al., 2008; Bowman et al., 2009). Fires play a dominant role in driving forest dynamics in many parts of the world; forest susceptibility to fire is projected to change little for the lowest emissions scenario (RCP2.6), but substantially for the high emissions scenario (RCP8.5; Figure 4-6). There is *low agreement* on whether climate change will cause fires to become more or less frequent in individual locations (Figure 4-6). Climate change-mediated disease and insect outbreaks could exacerbate climate-driven increases in fire susceptibility (Kurz et al., 2008). The greatest risks for large positive feedbacks from forests to climate through changes in disturbance regimes arise from widespread tree mortality and fire in tropical forests and low-latitude areas of boreal forests, as well as northward expansion of boreal forests into Arctic tundra (Lenton et al., 2008; Kriegler et al., 2009; Good et al., 2011b).

Recent evidence suggests (*low confidence*) that the stimulatory effects of global warming and rising CO_2 concentrations on tree growth may have already peaked in many regions (Charru et al., 2010; Silva et al., 2010; Silva and Anand, 2013) and that warming and changes in precipitation are increasing tree mortality in a wide range of forest systems, acting via heat stress, drought stress, pest outbreaks, and a wide range of other indirect impact mechanisms (Allen, C.D. et al., 2010; Box 4-2). Detection of a coherent global signal is hindered by the lack of long-term observations in many regions and attribution to climate change is difficult because of the multiplicity of mechanisms mediating mortality (Allen, C.D. et al., 2010).

Deforestation has slowed over the last decade (Meyfroidt and Lambin, 2011). This includes substantial reductions in tropical deforestation in some regions, such as the Brazilian Amazon, where deforestation rates declined rapidly after peaking in 2005 (Nepstad et al., 2009; INPE, 2013). Growing pressure for new crop (Section 4.4.4) and grazing land will continue to drive tropical deforestation (*medium confidence*), although recent policy experiments and market-based interventions in land use demonstrate the potential to reduce deforestation (Meyfroidt and Lambin, 2011; Westley et al., 2011; Nepstad et al., 2013).

4.3.3.1.1. Boreal forests

Most projections suggest a poleward expansion of forests into tundra regions, accompanied by a general shift in composition toward more temperate plant functional types (e.g., evergreen needleleaf being replaced by deciduous broadleaf; or in colder regions, deciduous needleleaf replaced by evergreen needleleaf (Lloyd et al., 2011; Pearson et al., 2013). Projections of climate-driven changes in boreal forests over the next few centuries remain uncertain on some issues, partly as a result of different processes of change being considered in different models. In particular, the inclusion or exclusion of fire and insects makes a big difference, possibly making the boreal forest more susceptible to a rapid, nonlinear, or abrupt decline in some regions (Bernhardt et al., 2011; Mann et al., 2012; Scheffer et al., 2012; see WGI AR5 Chapter 12). Recent observed change (Box 4-2) and dynamic vegetation modeling (e.g., Sitch et al., 2008) suggest that regions of the boreal forest could experience widespread forest dieback, although there is *low confidence* owing to conflicting results (Sitch et al., 2008; Gonzalez et al, 2010) and poor understanding of relevant mechanisms (WGI AR5 Section 12.5.5.6). If such shifts were to occur, they would put the boreal carbon sink at risk (Pan et al., 2011; Mann et al., 2012).

Whereas boreal forest productivity has been expected to increase as a result of warming (Hari and Kulmata, 2008; Bronson et al., 2009; Zhao and Running, 2010; Van Herk et al., 2011), and early analyses of satellite observations confirmed this trend in the 1980s (*medium confidence*), more recent and longer-term assessments indicate with *high confidence* that many areas of boreal forest have instead experienced productivity declines (*high confidence*; Goetz et al., 2007; Parent and Verbyla, 2010; Beck, P.S.A. et al., 2011; de Jong et al., 2011). The best evidence to date indicates that these "browning trends" are due to warming-induced drought, specifically the greater drying power of air (vapor pressure deficit; Williams et al., 2013), inducing photosynthetic down-regulation of boreal tree species, particularly conifer species, most of which are not adapted to the warmer conditions (Welp et al., 2007; Bonan, 2008; Van Herk et al., 2011). Satellite evidence for warming-induced productivity declines has been corroborated by tree ring studies (Barber et al., 2000; Hogg et al., 2008; Beck, P.S.A. et al., 2011; Porter and Pisaric, 2011; Griesbauer and Green, 2012) and long-term tree demography plots in more continental and densely forested areas (Peng et al., 2011; Ma et al., 2012). Conversely, productivity has increased at the boreal-tundra ecotone, where more mesic (moist) conditions may be generating the expected warming-induced positive growth response (Rupp et al., 2001; McGuire et al., 2007; Goldblum and Rigg, 2010; Beck, P.S.A. et al., 2011). The complexity of boreal forest response also involves tree age and size, with younger trees and stands perhaps being more able to benefit from warming where other factors are not limiting (Girardin et al., 2011, 2012).

Where they occur, warming and drying, coupled with productivity declines, insect disturbance, and associated tree mortality, also favor greater fire disturbance (*high confidence*). The boreal biome fire regime has intensified regionally in recent decades, exemplified by increases in the extent of area burned but also a longer fire season and more episodic fires that burn with greater energy output or intensity (Girardin and Mudelsee, 2008; Macias Fauria and Johnson, 2008; Kasischke et al., 2010; Turetsky et al., 2011; Mann et al., 2012; Girardin et al., 2013a). The latter is particularly important because more severe burning consumes soil organic matter to greater depth, often to mineral soil, providing conditions that favor recruitment of deciduous species that in some regions of the North American boreal forest replace what was previously evergreen conifer forest (Johnstone et al., 2010; Bernhardt et al., 2011). Fire-mediated composition changes in post-fire succession influence a host of ecosystem feedbacks to climate, including changes in net ecosystem carbon balance (Bond-Lamberty et al., 2007; Goetz et al., 2007; Welp et al., 2007; Euskirchen et al., 2009) as well as albedo and energy balance (Randerson et al., 2006; Jin et al., 2012; O'Halloran et al., 2012). The extent to which the net effect of these feedbacks will exacerbate or mitigate additional warming is not well known over the larger geographic domain of the boreal biome, except via modeling studies that are relatively poorly constrained owing to sparse *in situ* observations.

The vulnerability of the boreal biome to this cascading series of interacting processes (Wolken et al., 2011), and their ultimate influence on climate

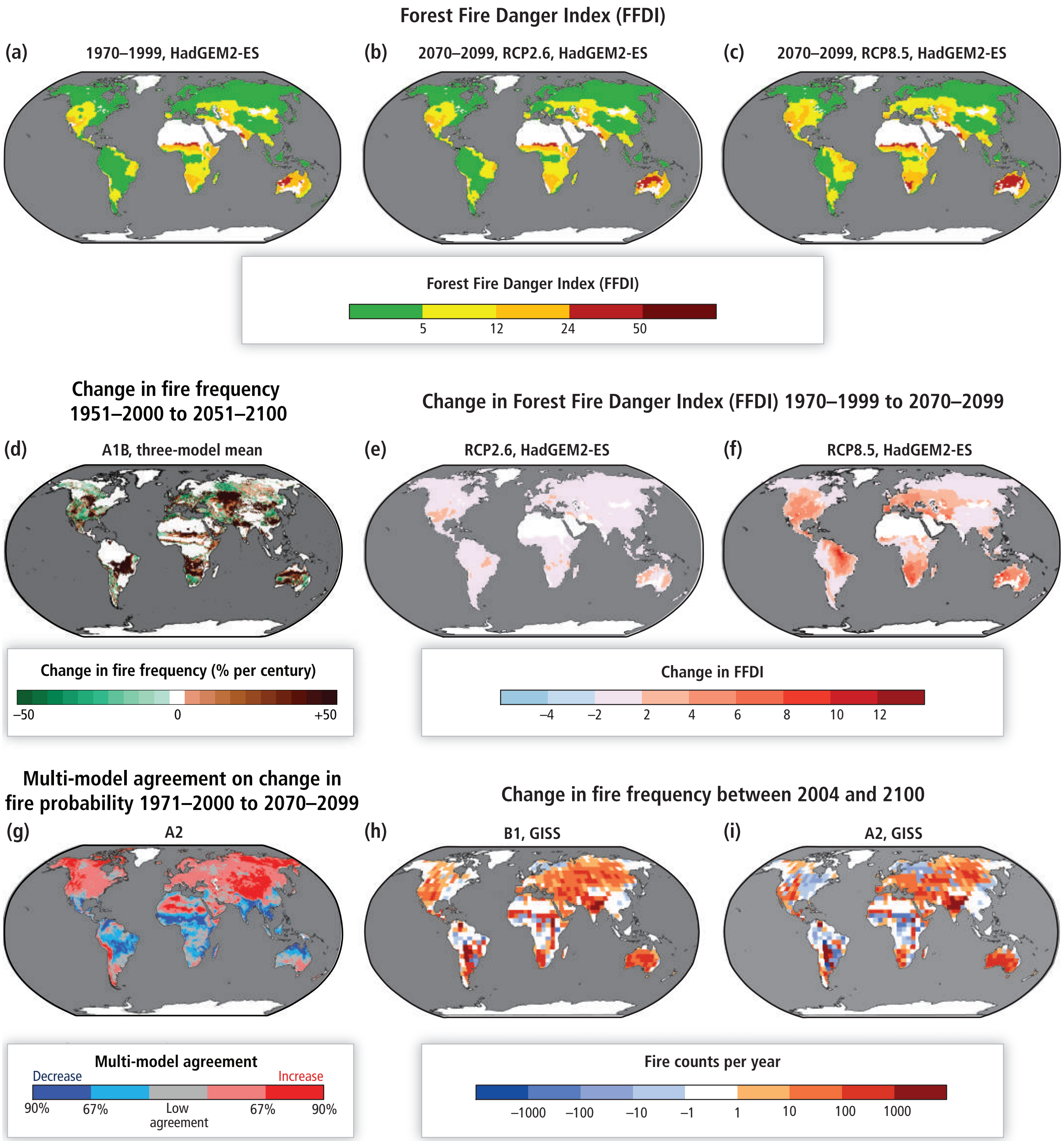

Figure 4-6 | Projected changes in meteorological fire danger, fire probability, and fire frequency with different methods and climate models. (a) 30-year annual mean McArthur Forest Fire Danger Index (FFDI) and change simulated with the Hadley Centre Global Environmental Model version 2 Earth System configuration (HadGEM2-ES) for 1970–1999, with areas of no vegetation excluded (Betts et al., 2013). (b) As (a) for 2070–2099, Representative Concentration Pathway 2.6 (RCP2.6). (c) as (a) for 2070–2099, RCP8.5. (d) Change in fire frequency by 2051–2100 relative to 1951–2000, SRES A1B, simulated with the MC1 vegetation model driven by three GCMs (Commonwealth Scientific and Industrial Research Organisation (CSIRO)-Mk3.0, Met Office Hadley Centre Coupled Model version 3 (HadCM3), Model for Interdisciplinary Research On Climate (MIROC) 3.2medres; mean over three simulations; Gonzalez et al., 2010). (e) Difference between (b) and (a): change in FFDI by 2070–2099 relative to 1970–1999 in HadGEM2-ES, RCP2.6. (f) Difference between (c) and (a): change in FFDI by 2070–2099 relative to 1970–1999 in HadGEM2-ES, RCP8.5. (g) Agreement on changes in fire probability by 2070–2099 relative to 1971–2000 (Moritz et al., 2012) simulated with a statistical model using climate projections from 16 Coupled Model Intercomparison Project Phase 3 (CMIP3) GCMs, Special Report on Emission Scenarios (SRES) A2. (h) Change in fire frequency by 2100 relative to 2004, SRES B1, simulated using climate and land cover projections from the Goddard Institute of Space Studies General Circulation Model (GISS GCM) (AR4 version) and Integrated Model to Assess the Global Environment Integrated Assessment Model (IMAGE IAM) (Pechony and Shindell, 2010). (i) As (h) for SRES A2. Changes in FFDI (a), (b), (c), (e), (f) and fire probability (g) arise entirely from changes in meteorological quantities, whereas changes in fire frequency (d), (h), (i) depend on both meteorological quantities and vegetation.

feedbacks, differs between North America and northern Eurasia (*high confidence*). The latter is dominated by deciduous conifer (larch) forest, extending from western Russia across central to eastern Siberia—a region more than twice the size of the North American boreal biome, most of it underlain by permafrost. In terms of post-fire succession analogous to the North American boreal biome, larch function more like deciduous species than evergreen conifers, with greater density and biomass gain in more severely burned areas, given adequate seed survival through fire events or post-fire seed dispersal (Zyryanova, 2007; Osawa et al., 2010; Alexander et al., 2012). Although the fire regime has intensified in the last 100 years in Siberia, as well as in parts of North America (Soja et al., 2007; Ali et al., 2012; Mann et al., 2012; Marlon et al., 2013), the likelihood of regime shifts in larch forests is currently unknown, partly because larch are self-replacing (albeit at different densities) and partly because it is largely dependent on the fate of permafrost across the region. In summary, an increase in tree mortality is observed in many boreal forests, with the clearest indicators of this in North America. However, tree health in boreal forests varies greatly among regions, which coupled with insufficient temporal coverage means that there is *low confidence* in the detection and attribution of a clear temporal trend in tree mortality at the global scale (Figure 4-4).

The vulnerability of permafrost to thawing and degradation with climate warming is critical not only for determining the rate of a boreal-tundra biome shift and its associated net feedback to climate, but also for predicting the degree to which the mobilization of very large carbon stores frozen for centuries could provide additional warming (*high confidence*; Schuur et al., 2008, 2009, 2013; Tarnocai et al., 2009; Romanovsky et al., 2010; Schaefer et al., 2011; see WGI AR5 Chapters 6 and 12; see also Section 4.3.3.4). The extent and rate of permafrost degradation varies with temperature gradients from warmer discontinuous permafrost areas to colder, more continuous areas, but also with the properties of the soil composition and biology (e.g., Mackelprang et al., 2011). The degree of thermokarsting (melting of ice-rich soil) associated with different substrates and associated topographic relief is variable because boreal vegetation in later successional stages (evergreen conifers in North America) insulates permafrost from air temperature increases; soils with differing silt and gravel content tend to have different ice content that, when melted, produces different degradation and deformation rates; and because of other factors such as the reduction of insulation provided by vegetation cover and soil organic layers due to increased fire (Jorgenson et al., 2010; Grosse et al., 2011). This variability and vulnerability is poorly represented in ESMs (McGuire et al., 2012) and is thus the emphasis of research initiatives currently underway. Carbon management strategies to keep permafrost intact, for example, by removing forest cover to expose the land surface to winter temperatures (Zimov et al., 2009), are impractical, not only because of the vast spatial domain underlain by permafrost, but also because of the broad societal and ecological impacts that would result.

4.3.3.1.2. Temperate forests

The largest areas of temperate forest are found in eastern North America, Europe, and eastern Asia. The overall trend for forests in these regions has until recently been an increase in growth rates of trees and in total carbon stocks. This has been attributed to a combination of increasing growing season length, rising atmospheric CO_2 concentrations, nitrogen deposition, and forest management—specifically regrowth following formerly more intensive harvesting regimes (Ciais et al., 2008). The relative contribution of these factors has been the subject of substantial and unresolved debate (Boisvenue and Running, 2006). Most temperate forests are managed such that any change is and will be to a large extent anthropogenic.

The world's temperate forests act as an important carbon sink (*high confidence* due to *robust evidence* and *high agreement*), absorbing 0.70 ± 0.08 PgC yr^{-1} from 1990 to 1999 and 0.80 ± 0.09 from 2000 to 2007 (Pan et al., 2011).This represents 34% of global carbon accumulation in intact forests and 65% of the global net forest carbon sink (total sink minus total emissions from land use).

Recent indications are that temperate forests and trees are beginning to show signs of climate stress, including a reversal of tree growth enhancement in some regions (North America: Silva et al., 2010; Silva and Anand, 2013; Europe: Charru et al., 2010; Bontemps et al., 2011; Kint et al., 2012); increasing tree mortality (Allen, C.D. et al., 2010; Box 4-2); and changes in fire regimes, insect outbreaks, and pathogen attacks (Adams et al., 2012; Edburg et al., 2012). In northeastern France, widespread recent declines in growth rates of European beech (*Fagus sylvatica* L.) have been attributed to decreasing water availability (Charru et al., 2010). These trends threaten the substantial role of temperate forests as net carbon sinks, but it is still unclear to what extent the observations are representative for temperate forests as a whole. Several studies find that tree growth rates in temperate forests passed their peak in the late 20th century and that the decline in tree growth rates can be attributed to climatic factors, especially drought or heat waves (Charru et al., 2010; Silva et al., 2010). Extreme climate events have had a major impact on temperate forests over the last decade (Ciais et al., 2005; Witte et al., 2011; Kasson and Livingston, 2012). Extensive forest fires occurred in Russia during the exceptionally hot and dry summer of 2010 (Witte et al., 2011). The complex interactions between climate and forest management in determining susceptibility to extreme events make it difficult to unequivocally attribute these events to recent climate warming (Allen, C.D. et al., 2010). There is *low confidence* (*limited evidence*, *medium agreement*) that climate change is threatening the temperate forest carbon sink directly or indirectly.

At the biome level, there remains considerable uncertainty in the sign and the magnitude of the carbon cycle response of temperate forests to climate change. A comparison of Dynamic Global Vegetation Models (DGVMs) showed that for identical end of 21st century climate projections, temperate forests are variously projected to substantially increase in total (biomass plus soil) carbon storage, especially through gains in forest cover; or decrease due to reductions in total carbon storage per hectare and loss of tree cover (Sitch et al., 2008). Projections for eastern Asia are less variable: temperate forests remain carbon sinks over the coming century, with carbon storage generally peaking by mid-century and then declining (Sitch et al., 2008; Peng et al., 2009; Ni, 2011). However, regional vegetation models for China predict a substantial northward shift of temperate forest (Weng and Zhou, 2006; Ni, 2011). There is little indication from either models or observations that the responses of temperate forests to climate change

Box 4-2 | Tree Mortality and Climate Change

Extensive tree mortality and widespread forest dieback (high mortality rates at a regional scale) linked to drought and temperature stress have been documented recently on all vegetated continents (Allen, C.D. et al., 2010; Figure 4-7). However, appropriate field data sets are currently lacking for many regions (Anderegg et al., 2013a), leading to *low confidence* in our ability to detect a global trend. Nevertheless, long-term increasing tree mortality rates associated with temperature increases and drought have been documented in boreal and temperate forests in western North America (van Mantgem et al., 2009; Peng et al., 2011). Increased levels of tree mortality following drought episodes have also been detected in multiple tropical forests (Kraft et al., 2010; Phillips et al., 2010) and Europe (Carnicer et al., 2011). Episodes of widespread dieback (high mortality rates at a regional scale) have been observed in multiple vegetation types, particularly in western North America, Australia, and southern Europe (Raffa et al., 2008; Carnicer et al., 2011; Anderegg et al., 2013a). Some widespread dieback events have occurred concomitant with infestation outbreaks (Hogg et al., 2008; Raffa et al., 2008; Michaelian et al., 2011), where insect populations are also directly influenced by climate, such as population release by warmer winter temperatures (Bentz et al., 2010). Although strong attribution of extensive tree mortality to recent warming has been made in a few studies, the paucity of long-term studies of the mechanisms driving mortality means that there is low confidence that this attribution can be made at the global scale.

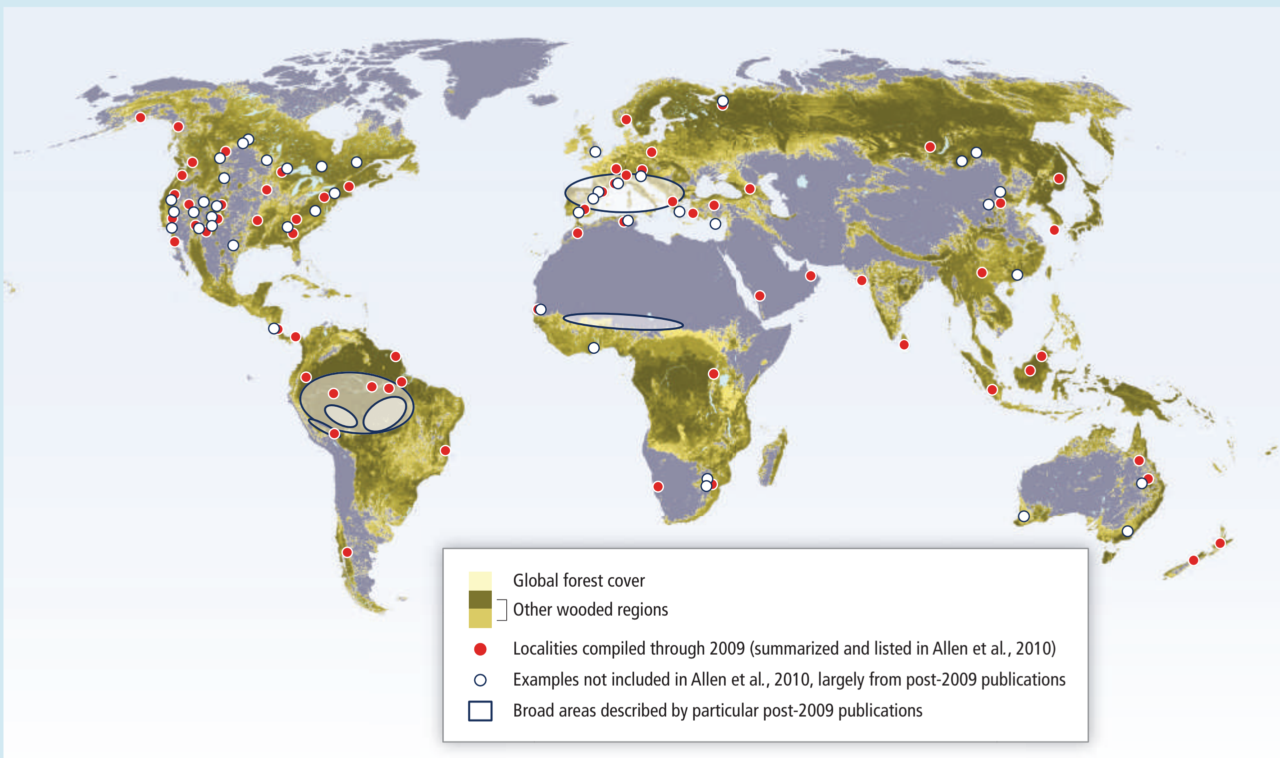

Figure 4-7 | Locations of substantial drought- and heat-induced tree mortality around the globe since 1970 (global forest cover and other wooded regions based on FAO, 2005). Studies compiled through 2009 (red dots) are summarized and listed in Allen, C.D. et al. (2010). Localities and measurement networks not included in Allen, C.D. et al. (2010), which are largely from post-2009 publications, have been added to this map (white dots and shapes). New locality references by region: Africa: Mehl et al., 2010; van der Linde et al., 2011; Fauset et al., 2012; Gonzalez et al., 2012; Kherchouche et al., 2012; Asia: Dulamsuren et al., 2009; Kharuk et al., 2013; Liu et al., 2013; Zhou et al., 2013; Australasia: Brouwers et al., 2012; Fensham et al., 2012; Keith et al., 2012; Matusick et al., 2012; Brouwers et al., 2013; Matusick et al., 2013; Europe: Innes, 1992; Peterken and Mountford, 1996; Linares et al., 2009; Galiano et al., 2010; Vennetier and Ripert, 2010; Aakala et al., 2011; Carnicer et al., 2011; Linares et al., 2011; Sarris et al., 2011; Marini et al., 2012; Cailleret et al., 2013; Vilà-Cabrera et al., 2013; North America: Fahey, 1998; Minnich, 2007; Klos et al., 2009; Ganey and Vojta, 2011; Michaelian et al., 2011; Peng et al., 2011; DeRose and Long, 2012; Fellows and Goulden, 2012; Kaiser et al., 2012; Millar et al., 2012; Garrity et al., 2013; Kukowski et al., 2013; Williams et al., 2013; Worrall et al., 2013; South America: Enquist and Enquist, 2011; Lewis et al., 2011; Saatchi et al., 2013.

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Box 4-2 (continued)

Forest dieback has influenced the species composition, structure and age demographics, and successional trajectories in affected forests, and in some cases led to decreased plant species diversity and increased risk of invasion (Kane et al., 2011; Anderegg et al., 2012). Widespread tree mortality also has multiple effects on biosphere-atmosphere interactions and could play an important role in future carbon-cycle feedbacks through complex effects on forest biophysical properties and biogeochemical cycles (Breshears et al., 2005; Kurz et al., 2008; Anderson et al., 2011).

Projections of tree mortality due to climate stress and potential thresholds of widespread forest loss are currently highly uncertain (McDowell et al., 2011). Most current vegetation models have little-to-no mechanistic representation of tree mortality (Fisher et al., 2010; McDowell et al., 2011). Nonetheless, a global analysis of tree hydraulic safety margins found that 70% of surveyed tree species operate close to their limits of water stress tolerance (Choat et al., 2012), indicating that vulnerability to drought and temperature stress will not be limited to arid and semiarid forests. Furthermore, time scales of tree and plant community recovery following drought are largely unknown, but preliminary evidence from several forests indicates that full recovery times may be longer than drought return intervals, leading to "compounding" effects of multiple droughts (Mueller et al., 2005; Anderegg et al., 2013b; Saatchi et al., 2013). Projected increases in temperature are also expected to facilitate expansion of insect pest outbreaks poleward and in altitude, which may also cause or contribute to tree mortality (Bentz et al., 2010).

are characterized by tipping points (Bonan, 2008). There is *low confidence* (*medium evidence*, *low agreement*) on long-term, climate-driven changes in temperate forest biomass and geographical range shifts.

At the species level, models predict that the potential climatic space for most tree species will shift poleward and to higher altitude in response to climate change (Dale et al., 2010; Ogawa-Onishi et al., 2010; Hickler et al., 2012). Associated long-term projected range shifts generally vary from several kilometers to several tens of kilometers per decade, most probably faster than natural migration (e.g., Chmura et al., 2011; see also Section 4.3.2.5). Therefore, assisted migration has been suggested as an adaptation measure (see Section 4.4.2.4). Such shifts would alter biodiversity and ecosystem services from temperate forests (e.g., Dale et al., 2010). Multi-model comparisons for temperate forests, however, illustrate that there are differences in species response and that models differ greatly in the severity of projected climate change impacts on species ranges (Morin and Thuiller, 2009; Kearney et al., 2010; Kramer et al., 2010; Cheaib et al., 2012). Tree growth models project increased tree growth at the poleward and high altitudinal range limits over most of the 21st century in China (Ni, 2011). New approaches to modeling tree responses, based on the sensitivity of key life-history stages, suggest that climate change impacts on reproduction could be a major limitation on temperate tree distributions (Morin et al., 2007). Comparisons with paleoecological data have helped improve confidence in the ability of models to project future changes in species ranges (Pearman et al., 2008; Allen, J.R.M. et al., 2010; Garreta et al., 2010). Model projections are qualitatively coherent with observations that temperate forest species are moving up in altitude, probably due to climate warming at the end of the 20th century (Lenoir et al., 2008). There is *medium confidence* (*medium evidence*, *medium agreement*) that temperate tree species are migrating poleward and to higher altitudes.

4.3.3.1.3. Tropical forests

Climate change effects on tropical forests interact with the direct influences of humans and are understood largely through field studies of the responses of forests to extreme weather events and through models that are able to simulate a growing number of ecological and atmospheric processes (Malhi et al., 2008; Davidson et al., 2012).

A key uncertainty in our understanding of future impacts of climate change on tropical forests is the strength of direct CO_2 effects on photosynthesis and transpiration (see Section 4.3.2.4). These responses will play an important role in determining tropical forest trends as temperatures and atmospheric CO_2 concentrations rise. There is a physiological basis for arguing that photosynthesis will increase sufficiently to offset the inhibitory effects of higher temperatures on forest productivity (Lloyd and Farquhar, 2008), although heightened photosynthesis does not necessarily translate into an increase in overall forest biomass (Körner and Basler, 2010). DGVMs and the current generation of ESMs, including those used within CMIP5 (e.g., Jones et al., 2011; Powell et al., 2013), generally use formulations for CO_2 effects on photosynthesis and transpiration based on laboratory-scale work (Jarvis, 1976; Farquhar et al., 1980; Ball et al., 1987; Stewart, 1988; Collatz et al., 1992; Leuning, 1995; Haxeltine and Prentice, 1996; Cox et al., 1998) that predates larger ecosystem-scale studies, although some models have been calibrated on the basis of more recent data (Jones et al., 2011).

A second important source of uncertainty is the rate of future CO_2 rise and climate change (Betts et al., 2012). Modeled simulations of future climate in tropical forest regions indicate with *high confidence* (*robust evidence*, *high agreement*) that temperature will increase. Future precipitation change, in contrast, is highly uncertain and varies considerably between climate models (WGI AR5 Annex 1: Atlas of Global and Regional Climate Projections), although there is *medium confidence* (*medium evidence*, *medium agreement*) that some tropical regions, such as the eastern Amazon Basin, will experience lower precipitation and more severe drought (Malhi et al., 2009a; Shiogama et al., 2011). The range of possible shifts in the moist tropical forest envelope is large, sensitive to the responsiveness of water use efficiency (WUE) to rising concentrations of atmospheric CO_2, and varies depending on the climate and vegetation model that is used (Scholze et al., 2006; Sitch et al., 2008; Zelazowski et al., 2011). Recent model studies (Malhi et al., 2009a; Cox et al., 2013; Huntingford et al., 2013) indicate that the future geographical range of moist tropical forests as determined by its shifting climatological envelope is less likely to undergo major retractions or expansions by 2100 than was suggested in AR4. Since AR4, there is new evidence of more frequent severe drought episodes in the Amazon region that are associated with sea surface temperature increases in the tropical North Atlantic (*medium confidence*; Marengo et al., 2011). There is *low confidence*, however, that these droughts or the observed sea surface temperatures can be attributed to climate change.

Networks of long-term forest plots reveal that lianas and fast-growing tree species are increasing, as is forest biomass (Phillips et al., 2002, 2005; Lewis et al., 2009a,b, 2011). Faster tree growth is consistent with increasing WUE associated with the rising concentration of CO_2, but also with changes in solar radiation and the ratio of diffuse to direct radiation (Lewis et al., 2009a; Mercado et al., 2009; Brando et al., 2010; see also Section 4.2.4.5). There is *low confidence* (*limited evidence*, *medium agreement*) that the composition and biomass of Amazon and African forests are changing through the rise in atmospheric CO_2. The potential suppression of photosynthesis and tree growth in tropical forests through rising air temperatures is supported by physiological and eddy covariance studies (Doughty and Goulden, 2008; Lloyd and Farquhar, 2008; Wood et al., 2012), but is not yet observed as changes in forest biomass (except Clark et al., 2003).

Since AR4, there is new experimental and observational evidence of ecological thresholds of drought and fire in moist tropical forests that points to an important indirect role of climate change in driving large-scale changes in these ecosystems, and to the importance of extreme drought events (see Box 4-3). Forest tree mortality increased abruptly above a critical level of soil moisture depletion in two rainfall exclusion experiments (Nepstad et al., 2007; Fisher et al., 2008) and above a critical level of weather-related fire intensity in a prescribed burn experiment (Brando et al., 2012). These experimental results were corroborated by observations of increased tree mortality during the severe 2005 drought in the Amazon (Phillips et al., 2009) and extensive forest fire (Alencar et al., 2006, 2011; Aragão et al., 2008; Box 4-3). There is *high confidence* (*medium evidence*, *high agreement*) that moist tropical forests have many tree species that are vulnerable to drought- and fire-induced mortality during extreme dry periods.

There is also a growing body of evidence that severe weather events interact with land use to influence moist tropical forest fire regimes. Many moist tropical forests are not susceptible to fire during typical rainfall years because of high moisture content of fine fuels (Cochrane, 2003). Selective logging, drought, and fire itself can reduce this fire resistance by killing trees, thinning the canopy, and allowing greater heating of the forest interior (Uhl and Kauffman, 1990; Curran et al., 2004; Ray et al., 2005; Box 4-3). Land use also often increases the ignition sources in tropical landscapes (Silvestrini et al., 2011). These relationships are not yet represented fully in coupled climate-vegetation models. There is *high confidence* (*robust evidence*, *high agreement*) that forest fire frequency and severity is increasing through the interaction between severe droughts and land use. There is *medium confidence* (*medium evidence*, *high agreement*) that tree mortality in the Amazon region is increasing through severe drought and increased forest fire occurrence and *low confidence* that this can be attributed to warming (Figure 4-4).

Dry tropical forests are defined by strong seasonality in rainfall distribution (Mooney et al., 1995) and have been reduced to an estimated 1 million km^2 globally through human activities (Miles et al., 2006). Half of the world's remaining dry tropical forests are located in South America. Using five climate model simulations for the 2040–2069 period under the IS92a "business-as-usual scenario," Miles et al. (2006) found that approximately one-third of the remaining area of tropical dry forests in the Americas will be exposed to higher temperatures and lower rainfall through climate change. Climate change, deforestation, fragmentation, fire, or human pressure place virtually all (97%) of the remaining tropical dry forests at risk of replacement or degradation (Miles et al., 2006). In a regional study a dynamic vegetation model (Integrated Biosphere Simulator (IBIS)) under A2 and B2 scenarios projected by a global climate model (Hadley Centre Regional Model 3 (HadRM3)) found that most of the dry forests of India would be outside of their climate envelopes later in this century (Chaturvedi et al., 2011). There is *low confidence* in our understanding of climate change effects on dry forests globally.

4.3.3.2. Dryland Ecosystems: Savannas, Shrublands, Grasslands, and Deserts

The following sections treat a wide range of terrestrial ecosystems covering a large part of the land surface, whose common features are that they typically exhibit strong water stress for several months each year and grass-like plants and herbs are a major part of their vegetation cover. Thus the principal land use often involves grazing by domestic livestock or wild herbivores.

4.3.3.2.1. Savannas

Savannas are mixtures of coexisting trees and grasses, covering about a quarter of the global land surface, including tropical and temperate forms. Savannas are characterized by annual to decadal fires (Archibald et al., 2009) of relatively low intensity, which are an important factor in maintaining the tree-grass proportions (Beerling and Osborne, 2006), but also constitute a major and climate-sensitive global source of fire-related emissions from land to atmosphere (Schultz et al., 2008; van der Werf et al., 2010). The geographical distribution of savannas is determined by temperature, the seasonal availability of water, fire, and soil conditions (Ellery et al., 1991; Walker and Langridge, 1997; Staver et al., 2011) and is therefore inferred to be susceptible to climate change. In parts of Central Africa, forests have been observed to be

Box 4-3 | A Possible Amazon Basin Tipping Point

Since AR4, our understanding of the potential of a large-scale, climate-driven, self-reinforcing transition of Amazon forests to a dry stable state (known as the Amazon "forest dieback") has improved. Modeling studies indicate that the likelihood of a climate-driven forest dieback by 2100 is lower than previously thought (Malhi et al., 2009b; Cox et al., 2013; Good et al., 2013; Huntingford et al., 2013), although lower rainfall and more severe drought is expected in the eastern Amazon (Malhi et al., 2009a). There is now *medium confidence* (*medium evidence*, *medium agreement*) that climate change alone (i.e., through changes in the climate envelope, without invoking fire and land use) will not drive large-scale forest loss by 2100 although shifts to drier forest types are predicted in the eastern Amazon (Mahli et al., 2009a). Meteorological fire danger is projected to increase in some models (Golding and Betts, 2008; Betts et al., 2013; Figure 4-6). Field studies and regional observations have provided new evidence of critical ecological thresholds and positive feedbacks between climate change and land use activities that could drive a fire-mediated, self-reinforcing dieback during the next few decades (Figure 4-8). There is now *medium confidence* (*medium evidence*, *high agreement*) that severe drought episodes, land use, and fire interact synergistically to drive the transition of mature Amazon forests to low-biomass, low-statured fire-adapted woody vegetation.

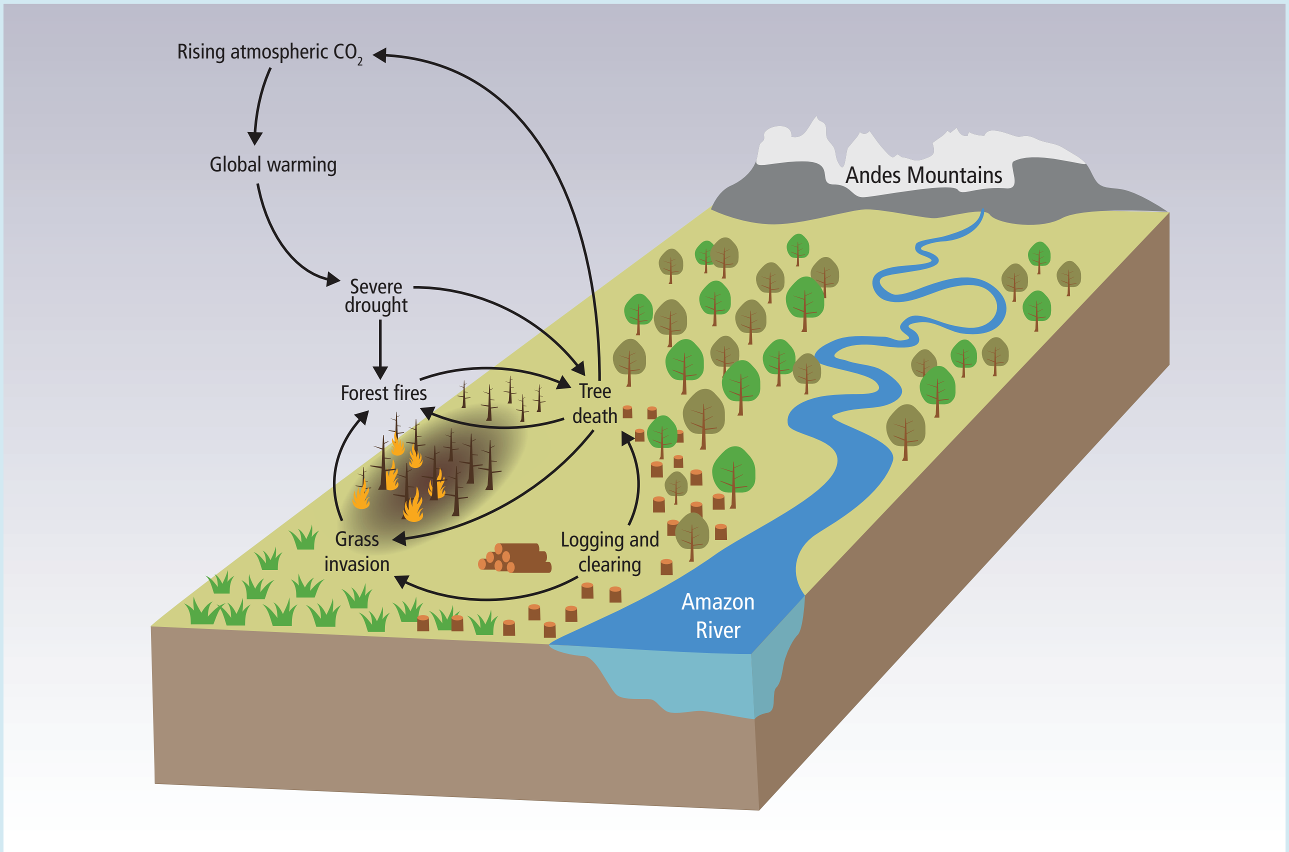

Figure 4-8 | The forests of the Amazon Basin are being altered through severe droughts, land use (deforestation, logging), and increased frequencies of forest fire. Some of these processes are self-reinforcing through positive feedbacks, and create the potential for a large-scale tipping point. For example, forest fire kills trees, increasing the likelihood of subsequent burning. This effect is magnified when tree death allows forests to be invaded by flammable grasses. Deforestation provides ignition sources to flammable forests, contributing to this dieback. Climate change contributes to this tipping point by increasing drought severity, reducing rainfall and raising air temperatures, particularly in the eastern Amazon Basin (*medium confidence*; *medium evidence*, *medium agreement*).

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Box 4-3 (continued)

Most primary forests of the Amazon Basin have damp fine fuel layers and low susceptibility to fire, even during annual dry seasons (Uhl and Kauffman, 1990; Ray et al., 2005). Forest susceptibility to fire increases through canopy thinning and greater sunlight penetration caused by tree mortality associated with selective logging (Uhl and Kauffman, 1990; Ray et al., 2005; Barlow and Peres, 2008), previous forest fire (Balch et al., 2008; Brando et al., 2012), severe drought (Alencar et al., 2006), or drought-induced tree mortality (Nepstad et al., 2007; da Costa et al., 2010). The impact of fire on tree mortality is also weather dependent. Under very dry, hot conditions, fire-related tree mortality can increase sharply (Brando et al., 2012). Under some circumstances, tree damage is sufficient to allow light-demanding, flammable grasses to establish in the forest understory, increasing forest susceptibility to further burning (Veldman and Putz, 2011). There is *high confidence* (*robust evidence*, *high agreement*) that logging, severe drought, and previous fire increase Amazon forest susceptibility to burning.

Landscape level processes further increase the likelihood of forest fire. Fire ignition sources are more common in agricultural and grazing lands than in forested landscapes (Silvestrini et al., 2011) (*high confidence*: *robust evidence*, *high agreement*), and forest conversion to grazing and crop lands can inhibit regional rainfall through changes in albedo and evapotranspiration (Costa et al., 2007; Butt et al., 2011; Knox et al., 2011) (*low confidence*: *medium evidence*, *low agreement*) or through smoke, which can inhibit rainfall under some circumstances (Andreae et al., 2004) (*medium confidence*: *medium evidence*, *medium agreement*). Apart from these landscape processes, climate change could increase the incidence of severe drought episodes (Mahli et al. 2009b; Shiogama et al., 2011).

If recent patterns of deforestation (through 2005), logging, severe drought, and forest fire continue into the future, more than half of the region's forests will be cleared, logged, burned, or exposed to drought by 2030, even without invoking positive feedbacks with regional climate, releasing 20 ± 10 PgC to the atmosphere (Nepstad et al., 2008) (*low confidence*: *low evidence*, *medium agreement*) (Figure 4-8). The likelihood of a tipping point being reached may decline if extreme droughts (such as 1998, 2005, and 2010) (Marengo et al., 2011) become less frequent, if land management fires are suppressed, if forest fires are extinguished on a large scale (Soares-Filho et al., 2012), if deforestation declines, or if cleared lands are reforested (Nepstad et al., 2008). The 77% decline in deforestation in the Brazilian Amazon with 80% of the region's forest still standing (INPE, 2013) demonstrates that policy-led avoidance of a fire-mediated tipping point is plausible.

moving into adjacent savannas and grasslands (Mitchard et al., 2009), possibly due to depopulation and changes in the fire regime. In northern Australia, forest is expanding into former savanna areas (Brook and Bowman, 2006; Bowman et al., 2011; Tng et al., 2012). It has been projected that drying and greater seasonality, acting in conjunction with increased fire, could lead to former forested areas becoming savannas in parts of the Amazon basin (Malhi et al., 2009b; Box 4-3). In many places around the world the savanna boundary is moving into former grasslands on elevation gradients; in other words, into areas inferred to be formerly too cool for trees (Breshears, 2006).

The proportion of trees and grasses in savannas is considered unstable under some conditions (De Michele et al., 2011; Staver et al., 2011). The differential effects of climate change, rising CO_2, fire, and herbivory on trees and grasses have the potential to alter the tree cover in savannas, possibly abruptly. There is evidence from many parts of the world that the tree cover and biomass in savannas has increased over the past century and in some places, on all continents, continues to do so (*robust evidence*, *high agreement*; Moleele et al., 2002; Angassa and Oba, 2008; Cabral et al., 2009; Wigley et al., 2009; Witt et al., 2009; Lunt et al., 2010; Rohde and Hoffman, 2012). The general consequences are more carbon stored per unit land area in form of tree biomass and soil organic matter (Hughes et al., 2006; Liao et al., 2006; Knapp et al., 2007; Throop and Archer, 2008; Boutton et al., 2009), changes in hydrology (Muñoz-Robles et al., 2011), and reduced grazing potential (Scholes and Archer, 1997). Increasing tree cover in savannas has been attributed to changes in land management (Joubert et al., 2008; Van Auken, 2009), rising CO_2 (Bond and Midgley, 2012; Buitenwerf et al., 2012), climate variability and change (Eamus and Palmer, 2007; Fensham et al., 2009), or several of these factors acting in combination (Ward, 2005). As yet, there are no studies that definitively attribute the relative importance of the climate- and non-climate-related causes of woody plant biomass increase in savannas (and the invasion of trees into former grasslands), but there is *medium agreement* and *robust evidence* that climate change and rising CO_2 are contributing factors in many cases. The increased growth rate of C_3 photosynthetic system trees relative to C_4

grasses under rising CO_2 could relieve the demographic bottleneck that keeps trees trapped within the flame zone of the grasses, a hypothesis supported by elevated CO_2 experiments with savanna saplings (Kgope et al., 2010).

A model of grasslands, savannas, and forests suggests that rising CO_2 does increase the likelihood of abrupt shifts to woodier states, but the transition will take place at different CO_2 concentrations in different environments (Higgins and Scheiter, 2012). On the other hand, observation of contrasts in the degree of savanna thickening between land parcels with the same CO_2 exposure but different land use histories, topographic position, or soil depth (Wiegand et al., 2005; Wu and Archer, 2005) imply that land management, water balance, and microclimate are also important. Tree cover in savannas is rainfall-constrained (Sankaran et al., 2005), suggesting that future increases in rainfall projected for most but not all savanna areas (WGI AR5 Annex I: Atlas of Global and Regional Climate Projections) could lead to increased tree biomass.

4.3.3.2.2. Grasslands and shrublands

Rangelands (partly overlapping with savannas) cover approximately 30% of the Earth's ice-free land surface and hold an equivalent amount of the world's terrestrial carbon (Booker et al., 2013). Much evidence from around the world shows that dry grasslands and shrublands are highly responsive in terms of primary production, species composition, and carbon balance to changes in water balance (precipitation and evaporative demand) within the range of projected climate changes (*high confidence*) (e.g., Sala et al., 1988; Snyman and Fouché, 1993; Fay et al., 2003; Peñuelas et al., 2004, 2007; Prieto et al., 2009; Peters et al., 2010; Martí-Roura et al., 2011; Booker et al., 2013; Wu and Chen, 2013). Rainfall amount and timing have large effects on a wide range of biological processes in grasslands and shrublands, including seed germination, seedling establishment, plant growth, flowering time, root mass, community composition, population and community dynamics production, decomposition and respiration, microbial processes and carbon, plant, and soil nutrient contents (e.g., Fay et al., 2003; Peñuelas et al., 2004, 2007; Beier et al., 2008; Sardans et al., 2008a,b; Sowerby et al., 2008; Liu et al., 2009; Miranda et al., 2009; Albert et al., 2011, 2012; Selsted et al., 2012; Walter et al., 2012).

Precipitation changes were as important for mountain flora in Europe as temperature changes, and the greatest composition changes will probably occur when decreased precipitation accompany warming (Engler et al., 2011). Responses of shrublands to drought may be driven partly by changes in the soil microbial community (Jensen et al., 2003) or changes in soil fauna (Maraldo et al., 2008). An increase in drought frequency, without an increase in drought severity, leads to loss of soil carbon in moist, carbon-rich moorlands, due to changes in soil structure or soil microbial community leading to increased hydrophobicity and soil respiration (Sowerby et al., 2008, 2010). Simulated increased spring temperature and decreased summer precipitation had a general negative effect on plant survival and plant growth, irrespective of the macroclimatic niche characteristics of the species. Against expectation, species with ranges extending into drier regions did not generally perform better under drier conditions (Bütof et al., 2012).

Changing climate and land use have resulted in increased aridity and a higher frequency of droughts in drylands around the world, with increasing dominance of abiotic controls of land degradation (in contrast to direct human- or herbivore-driven degradation) and changes in hydrology and the erosion of soil by wind (Ravi et al., 2010). In mixed shrub grasslands, the influence of drought periods could produce transient pulses of carbon that are much larger than the pulses produced by fire (Martí-Roura et al., 2011). Most studies of changes in arid systems between grasslands and shrublands have focused on plant-soil feedbacks that favor shrub growth. Summers drier than three-quarters of current rainfall decreased grass seedling recruitment to negligible values (Peters et al., 2010). Management cannot reliably increase carbon uptake in arid and semiarid rangelands, which is most often controlled by abiotic factors not easily changed by management of grazing or vegetation (Booker et al., 2013).

Other factors being equal, grasslands and shrublands in cool areas are expected to respond to warming with increased primary production, while those in hot areas are expected to show decreased production (*limited evidence*, *low agreement*). A shift to more woody vegetation states expected to occur (locally but not globally) in tropical grasslands of the African continent (Higgins and Scheiter, 2012). The response to warming and drought depends on site, year, and plant species, as shown by manipulation experiments (Peñuelas et al., 2004, 2007; Gao and Giorgi, 2008; Grime et al., 2008; Shinoda et al., 2010; Wu and Chen, 2013). In most temperate and Arctic regions, the capacity to support richer (i.e., more diverse) communities is projected to increase with rising temperature, while decreases in water availability suggest a decline in capacity to support species-rich communities in most tropical and subtropical regions (Sommer et al., 2010). Warming may cause an asymmetrical response of soil carbon and nitrogen cycles, causing nitrogen limitation that reduces acclimation in plant production (Beier et al., 2008).

Some grasslands are exposed to elevated levels of nitrogen deposition, which alters species composition, increases primary production up to a point, and decreases it thereafter (see Section 4.2.4.2; Bobbink et al., 2010; Cleland and Harpole, 2010; Gaudnik et al., 2011). In a study of 162 plots over 25 years, nitrogen deposition drove grassland composition at the local scale, in interaction with climate, whereas climate changes were the predominant driver at the regional scale (Gaudnik et al., 2011). Nitrogen mineralization in shrublands under either arid or wet conditions is more sensitive to periodic droughts than systems under more mesic conditions (Emmett et al., 2004). Decreased tissue concentrations of phosphorus were also associated with warming and drought (Peñuelas et al., 2004, 2012; Beier et al., 2008). Strong interactions between warming and disturbances have been observed, leading to increased nitrogen leaching from shrubland ecosystems (Beier et al., 2004).

Most grasslands and shrublands are characterized by relatively frequent but low-intensity fires, which affect their plant species composition and demographics (e.g., Gibson and Hulbert, 1987; Gill et al., 1999; Uys et al., 2004; de Torres Curth et al., 2012). Species composition changes may be as important in determining ecosystem impacts as the direct effects of climate on plant (Suttle et al., 2007). Fire frequency, duration, and intensity are influenced primarily by climate and secondarily by management (Pitman et al., 2007; Lenihan et al., 2008; Archibald et al., 2009; Giannakopoulos et al., 2009; Armenteras-Pascual et al., 2011), and are therefore sensitive to climate change; the duration of the fire season is also projected to broaden (Clarke et al., 2013). Changes in fire frequency may interact with changes in rainfall seasonality: for instance, if fires are followed by rainy spring periods in northwestern Patagonia, as occurs with more frequent El Niño-Southern Oscillation (ENSO) phenomena, there are more recruitment windows for shrubs (Ghermandi et al., 2010). Relatively little is known regarding the combined effect of climate change and increased grazing by large mammals, or on the consequences for pastoral livelihoods that depend on rangelands (Thornton et al., 2009).

4.3.3.2.3. Deserts

The deserts of the world, defined as land areas with an arid or hyperarid climate regime, occupy 35% of the global land surface. Species composition in desert areas is expected to shift in response to climate warming (Ooi et al., 2009; Kimball et al., 2010). Deserts are sparsely populated, but the people who do live there are among the poorest in the world (Millennium Ecosystem Assessment, 2005a). There is *medium agreement* but *limited evidence* that the present extent of deserts will increase in the coming decades, despite the projected increase in rainfall at a global scale, as a result of the strengthening of the Hadley Circulation, which determines the location of the broad band of hot deserts approximately 15°N to 30°N and 15°S to 30°S of the equator (Mitas and Clement, 2005; Seidel et al., 2008; Johanson and Fu, 2009; Lu et al., 2009; Zhou et al., 2011). There may be a feedback to the global climate from an increase in desert extent, which differs in sign between deserts closer to the equator than 20° and those closer to the pole: in model simulations, extension of the near-equator "hot deserts" causes warming, while extension of the near-boreal "cold deserts" causes cooling, in both cases largely through albedo-mediated effects (Alkama et al., 2012). Deserts are expected to become warmer and drier at faster rates than other terrestrial regions (Lapola et al., 2009; Stahlschmidt et al., 2011). Most deserts are already extremely hot, and therefore further warming likely to be physiologically injurious rather than beneficial. The ecological dynamics in deserts are rainfall event-driven (Holmgren et al., 2006), often involving the concatenation of a number of quasi-independent events. Some desert tolerance mechanisms (e.g., biological adaptations by long-lived taxa) may be outpaced by global climate change (Lapola et al., 2009; Stahlschmidt et al., 2011).

4.3.3.2.4. Mediterranean-type ecosystems

Mediterranean-type ecosystems occur on most continents, and are characterized by cool, wet winters and hot, dry summers. They were identified as being among the most likely to be impacted by climate change in AR4 and received extensive coverage (Fischlin et al., 2007). Since then, further evidence has accumulated of climate risks to these systems from rising temperature (Giorgi and Lionello, 2008), rainfall change (declining in most but not all cases), increased drought (Sections 23.2.3, 25.2), and increased fire frequency (Section 23.4.4). There have been observed shifts in phenology (Gordo and Sanz, 2010), range contraction of Mediterranean species (Pauli et al., 2012), declines in the health and growth rate of dominant tree species (Allen, C.D. et al., 2010; Sarris et al., 2011; Brouwers et al., 2012; see also Section 23.4.4), and increased risk of erosion and desertification, especially in very dry areas (Lindner et al., 2010; Shakesby, 2011). Model projections show further species range contractions in the 21st century under all climate change scenarios. This will result in losses of biodiversity (*medium confidence*) (Maiorano et al., 2011; Kuhlmann et al., 2012; see also Sections 23.6.4, 25.1).

4.3.3.3. Rivers, Lakes, Wetlands, and Peatlands

Freshwater ecosystems are considered to be among the most threatened on the planet (Dudgeon et al., 2006; Vörösmarty et al., 2010). Fragmentation of rivers by dams and the alteration of natural flow regimes have led to major impacts on freshwater biota (Pringle, 2001; Bunn and Arthington, 2002; Nilsson et al., 2005; Reidy Liermann et al., 2012). Floodplains and wetland areas have become occupied for intensive urban and agricultural land use to the extent that many are functionally disconnected from their rivers (Tockner et al., 2008). Pollution from cities and agriculture, especially nutrient loading, has resulted in declines in water quality and the loss of essential ecosystem services (Allan, 2004). As a direct consequence of these and other impacts, freshwaters have some of the highest rates of extinction of any ecosystem for those species groups assessed for the IUCN Red List (estimated as much as 4% per decade for some groups, such as crayfish, mussels, fishes, and amphibians in North America) (Dudgeon et al., 2006), with estimates that roughly 10,000 to 20,000 freshwater species are extinct or imperilled as a consequence of human activity (Strayer and Dudgeon, 2010). This is a particular concern given that freshwater habitats support 6% of all described species (Dudgeon et al., 2006), including approximately 40% of the world's fish diversity and a third of the vertebrate diversity (Balian et al., 2008).

It is *very likely* that these stressors to freshwater ecosystems will continue to dominate as human demand for water resources grows, accompanied by increased urbanization and expansion of irrigated agriculture (Vörösmarty et al., 2000; Malmqvist et al., 2008; Dise, 2009). However, climate change will have significant additional impacts (*high confidence*), from altered thermal regimes, altered precipitation and flow regimes, and, in the case of coastal wetlands, sea level rise. Specific aquatic habitats that are most vulnerable to these direct climate effects, especially rising temperatures, are those at high altitude and high latitude, including Arctic and sub-Arctic bog communities on permafrost, and alpine and Arctic streams and lakes (see Section 4.3.3.4; Klanderud and Totland, 2005; Smith et al., 2005; Smol and Douglas, 2007b). It is noteworthy that these high-latitude systems currently experience a relatively low level of threat from other human activities (Vörösmarty et al., 2010). It is likely that the shrinkage and disappearance of glaciers will lead to the reduction of local and regional freshwater biodiversity, with 11 to 38% of the regional macroinvertebrate species pool expected to be lost following complete disappearance of glaciers (Jacobsen et al., 2012; Box CC-RF). Shrinkage of glaciers and the loss of small glaciers will most likely reduce beta diversity at the species and the genetic level, as predicted for the Pyrenees (Finn et al., 2013). Dryland rivers and wetlands, many already experiencing severe water stress from human consumptive use, are also likely to be further impacted by decreased and more variable precipitation and higher temperatures. Headwater stream systems in general are also vulnerable to the effects of warming because their temperature regimes closely track air temperatures (Caissie, 2006).

There is widespread evidence of rising stream and river temperatures over the past few decades (Langan et al., 2001; Morrison et al., 2002; Webb and Nobilis, 2007; Chessman, 2009; Ormerod, 2009; Kaushal et al., 2010; van Vliet et al., 2011; Markovic et al., 2013; but see Arismendi et al., 2012). Rising water temperature has been linked by observational and experimental studies to shifts in invertebrate community composition, including declines in cold stenothermic species (Brown et al., 2007; Durance and Ormerod, 2007; Chessman, 2009; Ormerod, 2009). Rising temperature is also implicated in species range shifts (e.g., Comte and Grenouillet, 2013), implying changes in the composition of river fish communities (Daufresne and Boet, 2007; Buisson et al., 2008; Comte et al., 2013), especially in headwater streams where species are more sensitive to warming (e.g., Buisson and Grenouillet, 2009).

Rising temperatures in the well-mixed surface waters in many temperate lakes, resulting in reduced periods of ice formation (Livingstone and Adrian, 2009; Weyhenmeyer et al., 2011) and earlier onset and increased duration and stability of the thermocline during summer (Winder and Schindler, 2004), are projected to favor a shift in dominance to smaller phytoplankton (Parker et al., 2008; Winder et al., 2009; Yvon-Durocher et al., 2011) and cyanobacteria (Wiedner et al., 2007; Jöhnk et al., 2008; Paerl et al., 2011), especially in those ecosystems experiencing high anthropogenic loading of nutrients (Wagner and Adrian, 2009); with impacts to water quality, food webs, and productivity (O'Reilly et al., 2003; Verburg et al., 2003; Gyllström et al., 2005; Parker et al., 2008; Shimoda et al., 2011). Prolonged stratification and associated anaerobic conditions near the sediment-water interface can increase the internal loading of phosphorus, particularly in eutrophic lakes (Søndergaard et al., 2003; Wilhelm and Adrian, 2008; Wagner and Adrian, 2009).

In many freshwater ecosystems, the input of dissolved organic carbon through runoff from the catchment has increased, inducing changes in water color (Hongve et al., 2004; Evans et al., 2005; Erlandsson et al., 2008). Soil recovery from acidification and changed hydrological conditions (partly linked to increased precipitation) appear to be the main factors driving this development (Evans et al., 2005; Monteith et al., 2007). The resulting increased light attenuation can lead to lower algal concentrations and loss of submersed vegetation (Ask et al., 2009; Karlsson et al., 2009).

Emergent aquatic macrophytes are likely to expand their northward distribution and percentage cover in boreal lakes and wetlands, posing an increasing overgrowth risk for sensitive macrophyte species (Alahuhta et al., 2011). Long-term shifts in macroinvertebrate communities have also been observed in European lakes where temperatures have increased (Burgmer et al., 2007), noting that warming may increase species richness in smaller temperate water bodies, especially those at high altitude (Rosset et al., 2010). Although less studied, it has been proposed that tropical ectothermic ("cold blooded") organisms will be particularly vulnerable because they will approach critical maximum temperatures proportionately faster than species in high-latitude environments, despite lower rates of warming (Deutsch et al., 2008; Hamilton, 2010; Laurance et al., 2011).

There is growing evidence that climate-induced changes in precipitation will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (*high confidence* in detection, *medium confidence* in attribution; see Box CC-RF; Xenopoulos et al., 2005; Aldous et al., 2011). Freshwater ecosystems in Mediterranean-montane ecoregions (e.g., Australia, California, and South Africa) are projected to experience a shortened wet season and prolonged, warmer summer season (Klausmeyer and Shaw, 2009), increasing the vulnerability of fish communities to drought (Magalhães et al., 2007; Hermoso and Clavero, 2011) and floods (Meyers et al., 2010). Shifts in hydrologic regimes in snowmelt systems, including earlier runoff and declining base flows in summer (Stewart et al., 2005; Stewart, 2009), are projected to alter freshwater ecosystems, through changes in physical habitat and water quality (Bryant, 2009). Declining rainfall and increased interannual variability will most likely increase low-flow and dry-spell duration in dryland regions, leading to reduced water quality in remnant pools (Dahm et al., 2003), reduction in floodplain egg and seed banks (Capon, 2007; Jenkins and Boulton, 2007), the loss of permanent aquatic refugia for fully aquatic species and water birds (Johnson et al., 2005; Bond et al., 2008; Sheldon et al., 2010), altered freshwater food webs (Ledger et al., 2013), and drying out of wetlands (Davis, J.L. et al., 2010).

Climate-induced changes in precipitation will probably be an important factor altering peatland vegetation in temperate and boreal regions, with decreasing wetness during the growing season generally associated with a shift from a Sphagnum dominated to vascular plant dominated vegetation type and a general decline of carbon sequestration in the long term (Limpens et al., 2008). Mire ecosystems (i.e., bogs, transition bogs, and fens) in central Europe face severe climate-induced risk, with increased summer temperatures being particularly important (Essl et al., 2012). Decreased dry season precipitation and longer dry seasons in major tropical peatland areas in Southeast Asia are projected to result in lower water tables more often and for longer periods, with an increased risk of fire (Li et al., 2007; Rieley et al., 2008; Frolking et al., 2011).

Peatlands contain large stocks of carbon that are vulnerable to change through land use and climate change. Although peatlands cover only about 3% of the land surface, they hold the equivalent of half of the atmosphere's carbon (as CO_2), or one-third of the world's soil carbon stock (400 to 600 Pg) (Limpens et al., 2008; Frolking et al., 2011; Page et al., 2011). About 14 to 20% of the world's peatlands are currently used for agriculture (Oleszczuk et al., 2008) and many, particularly peat swamp forests in Southeast Asia, are undergoing rapid major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning (Limpens et al., 2008; Hooijer et al., 2010). Deforestation, drainage, and burning in Indonesian peat swamp forests can release 59.4 ± 10.2 Mg CO_2 ha^{-1} yr^{-1} over 25 years (Murdiyarso et al., 2010), contributing significantly to global GHG emissions, especially during periods of intense drought associated with ENSO when burning is more common (Page et al., 2002). Anthropogenic disturbance has changed peatlands from being a weak global carbon sink to a source (Frolking et al., 2011), though interannual variability is large. Fluvial export can also be a significant contributor to carbon losses that has been largely overlooked to date, with recent estimates of DOC export from degraded tropical peatlands 50% higher than in intact systems (Moore et al., 2013). Conserving peatland areas not yet developed for biofuels or other crops, or rewetting and restoring degraded peatlands to preserve their carbon store, are potential mitigation strategies.

Sea level rise will lead to direct losses of coastal wetlands with associated impacts on water birds and other wildlife species dependent on fresh water (BMT WBM, 2010; Pearlstine et al., 2010; Traill et al., 2010), but the impact will probably be relatively small compared with the degree of direct and indirect human-induced destruction (Nicholls, 2004). River deltas and associated wetlands are particularly vulnerable to rising sea level, and this threat is further compounded by trapping of sediment in reservoirs upstream and subsidence from removal of oil, gas, and water (Syvitski et al., 2009; see Section 5.4.2.7). Lower river flows might exacerbate the impact of sea level rise and thus salinization on freshwater ecosystems close to the ocean (Ficke et al., 2007).

4.3.3.4. Tundra, Alpine, and Permafrost Systems

The High Arctic region, with tundra-dominated landscapes, has warmed more than the global average over the last century (Kaufman et al., 2009; see WGI AR5 Chapter 2). Changes consistent with warming are evident in the freshwater and terrestrial ecosystems and permafrost of the region (Hinzman et al., 2005; Axford et al., 2009; Jia, G.J. et al., 2009; Post et al., 2009; Prowse and Brown, 2010; Romanovsky et al., 2010; Walker et al., 2012). Most of the Arctic has experienced recent change in vegetation photosynthetic capacity, particularly adjacent to rapidly retreating sea ice (Bhatt et al., 2010). Changes in terrestrial environments in Antarctica have also been reported. Vieira et al. (2010) show that in in the Maritime Antarctic permafrost temperatures are close to thaw. Permafrost warming has been observed in continental Antarctica (Guglielmin and Cannone, 2012) and for the Palmer archipelago (Bockheim et al., 2013).

Continued warming is projected to cause the terrestrial vegetation and lake systems of the Arctic to change substantially (*high confidence*). Continued expansion in woody vegetation cover in tundra regions over the 21st century is projected by the CMIP5 ESMs (Bosio et al., 2012; see WGI AR5 Chapter 6), by dynamic global vegetation models driven by other climate model projections, and by observationally based statistical models (Pearson et al., 2013). Changes may be complex (see Box 4-4) and in some cases involve nonlinear and threshold responses to warming and other climatic change (Hinzman et al., 2005; Mueller, D.R. et al., 2009; Bonfils et al., 2012). Arctic vegetation change is expected to continue long after any stabilization of global mean temperature (see WGI AR5 Chapter 6; Falloon et al., 2012). In some regions, reduced surface albedo due to increased vegetation cover is projected to cause further local warming even in scenarios of stabilized GHG concentrations (Falloon et al., 2012).

In the Arctic tundra biome (in contrast to the boreal forests discussed in Section 4.3.3.1.1), vegetation productivity has systematically increased over the past few decades in both North America and northern Eurasia (Goetz et al., 2007; Stow et al., 2007; Jia, G.J. et al., 2009; de Jong et al., 2011; Myers-Smith et al., 2011; Elmendorf et al., 2012). This phenomenon is amplified by retreat of coastal sea ice (Bhatt et al., 2010) and has been widely discussed in the context of increased shrub growth and expansion over the last half century (Forbes et al., 2010; Myers-Smith et al., 2011). Deciduous shrubs and graminoids respond to warming with increased growth (Walker, 2006; Epstein et al., 2008; Euskirchen et al., 2009; Lantz et al., 2010). Analyses of satellite time series data show the increased productivity trend is not unique to shrub-dominated tundra areas (Jia, G.J. et al., 2009; Beck and Goetz, 2011); thus greening is a response shared by multiple vegetation communities and continued changes in the tundra biome can be expected irrespective of shrub presence. The very large spatial scale over which these changes are occurring, the strong warming signal over much of the Arctic for the last 5 decades (Burrows et al., 2011), and the absence of strong confounding factors means that detection of these changes in Arctic systems and their attribution to global warming can be made with *high confidence*, despite the relatively short time frame of most observations (Figure 4-4).

Shrub expansion and height changes are particularly important because they trap snow, mediate winter soil temperature and summer moisture regimes, increase nutrient mineralization, and produce a positive feedback for additional shrub growth (Sturm et al., 2005; Lawrence et al., 2007; Bonfils et al., 2012). Although increased shrub cover and height produce shadowing that reduce ground heat flux and active layer depth, they also reduce surface albedo, increase energy absorption and evapotranspiration (Chapin III et al., 2005; Blok et al., 2010), and produce feedbacks that reinforce shrub densification and regional warming (Lawrence and Swenson, 2011; Bonfils et al., 2012). On balance, these feedbacks can act to partially offset one another, but when coupled with warmer and wetter conditions they act to increase active layer depth and permafrost thaw (Yi et al., 2007; Bonfils et al., 2012).

The Arctic tundra biome is experiencing increasing fire disturbance and permafrost degradation. Both of these processes facilitate conditions for woody species establishment in tundra areas, either through incremental migration or via more rapid long-distance dispersal to areas reinitialized by burning (Epstein et al., 2007; Goetz et al., 2011). When already present at the boreal-tundra ecotone, shrub and tree species show increased productivity with warmer conditions (Devi et al., 2008; Andreu-Hayles et al., 2011; Elmendorf et al., 2012). Tundra fires not only emit large quantities of combusted carbon formerly stored in vegetation and organic soils (Mack et al., 2011; Rocha and Shaver, 2011), but also increase active layer depth during summer months (Racine et al., 2004; Liljedahl et al., 2007; Jorgenson et al., 2010), produce landforms associated with thawing of ice-rich permafrost, and can create conditions that alter vegetation succession (Racine et al., 2004; Lantz et al., 2009; Higuera et al., 2011).

It is *virtually certain* that the area of NH permafrost will continue to decline over the first half of the 21st century (see WGI AR5 Chapter 12) in all RCP scenarios (Figure 4-9; Caesar et al., 2013; Koven et al., 2013). In the RCP2.6 scenario of an early stabilization of CO_2 concentrations, the permafrost area is projected to stabilize at a level approximately 20% below the 20th century area, and then begin a slight recovering trend. In RCP4.5, in which CO_2 concentration is stabilized at approximately 550 ppmv by the mid-21st century, the simulations that extend beyond 2100 show permafrost continuing to decline for at least another 250 years. In the RCP8.5 scenario of ongoing CO_2 rise, the permafrost area is simulated to approach zero by the middle of the 22nd century in

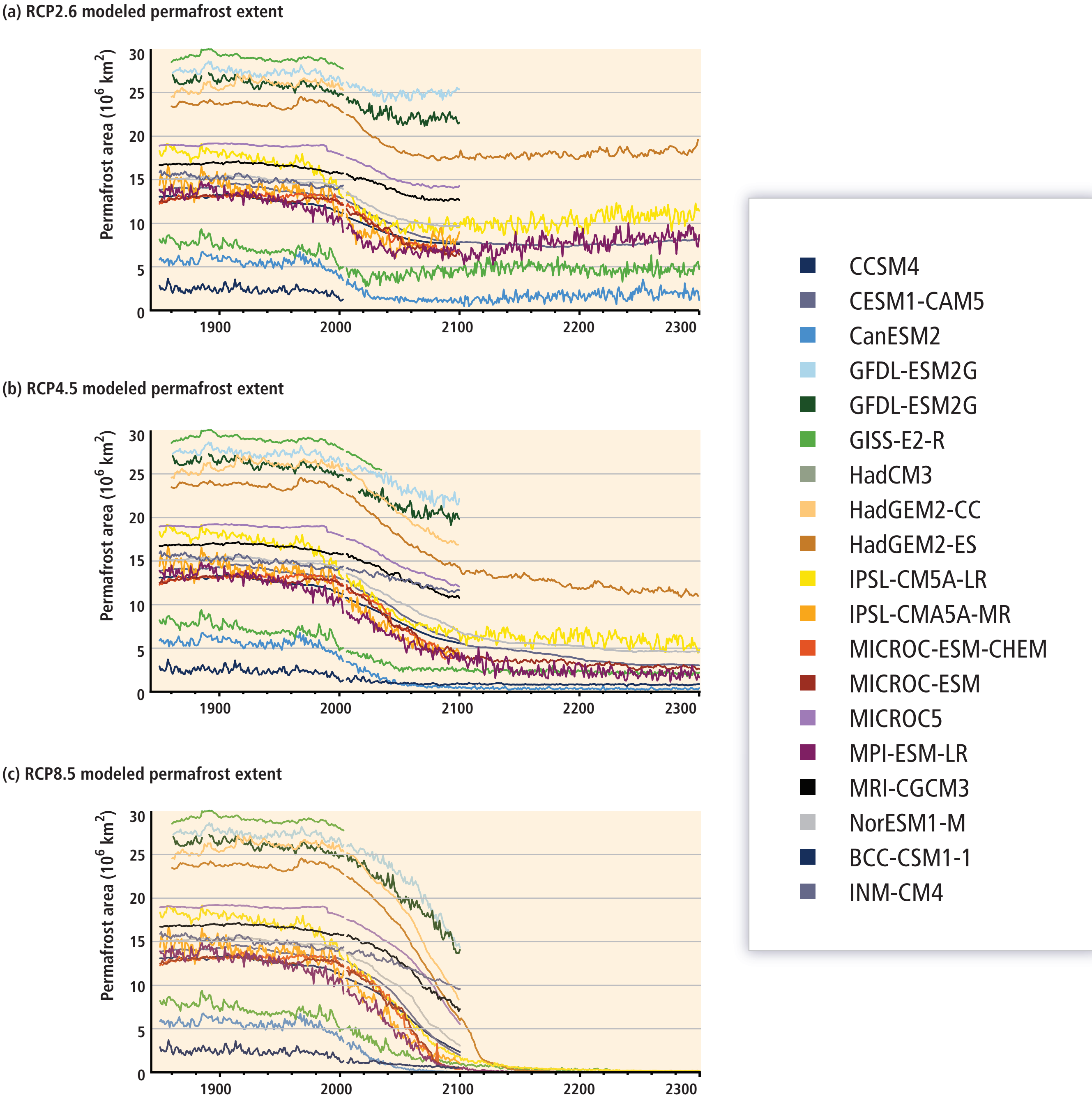

Figure 4-9 | CMIP5 multi-model simulated area of Northern Hemisphere permafrost in the upper 3 m of soil, from 1850 to 2100 or 2300 depending on extent of individual simulations. Each panel shows historical (1850–2005) and projected (2005–2100 or 2300) simulations for (a) Representative Concentration Pathway 2.6 (RCP2.6), (b) RCP4.5, and (c) RCP8.5. The observed current permafrost extent is 15 × 10^6 km^2. (Based on Koven et al., 2013, with analysis extended to 2300 following Caesar et al., 2013).

simulations that extend beyond 2100. RCP8.5 simulations that ended at 2100 showed continued permafrost decline in the late 21st century, although at slower rates in some cases as the remaining permafrost area decreases (Figure 4-9.).

Frozen soils and permafrost currently hold about 1700 PgC, more than twice the carbon than the atmosphere, and thus represent a particularly large vulnerability to climate change (i.e., warming) (see WGI AR5 Chapter 6). Although the Arctic is currently a net carbon sink, continued warming will act to turn the Arctic to a net carbon source, which will in turn create a potentially strong positive feedback to accelerate Arctic (and global) warming with additional releases of CO_2, CH_4, and perhaps N_2O, from the terrestrial biosphere into the atmosphere (*high confidence*; Schuur et al., 2008, 2009; Maslin et al., 2010; McGuire et al., 2010; O'Connor et al., 2010; Schaefer et al., 2011; see WGI AR5 Chapter 6 for detailed treatment of biogeochemistry, including feedbacks). Moreover, this feedback is already accelerating due to climate-induced increases in fire (McGuire et al., 2010; O'Donnell et al., 2011). The rapid retreat of snow cover and resulting spread of shrubs and trees into areas currently dominated by tundra has begun, and will continue to serve

Box 4-4 | Boreal-Tundra Biome Shift

Changes in a suite of ecological processes currently underway across the broader Arctic region are consistent with Earth System Model (ESM) predictions of climate-induced geographic shifts in the range extent and functioning of the tundra and boreal forest biomes (Figure 4-10). Until now, these changes have been gradual shifts across temperature and moisture gradients, rather than abrupt. Responses are expressed through gross and net primary production, microbial respiration, fire and insect disturbance, vegetation composition, species range expansion and contraction, surface energy balance and hydrology, active layer depth and permafrost thaw, and a range of other inter-related variables. Because the high northern latitudes are warming more rapidly than other parts of the Earth, due at least in part to Arctic amplification (Serreze and Francis, 2006), the rate of change in these ecological processes are sufficiently rapid that they can be documented *in situ* (Hinzman et al., 2005; Post et al., 2009; Peng et al., 2011; Elmendorf et al., 2012) as well as from satellite observations (Goetz et al., 2007; Beck, P.S.A. et al., 2011; Xu et al., 2013) and captured in ESMs (McGuire et al., 2010).

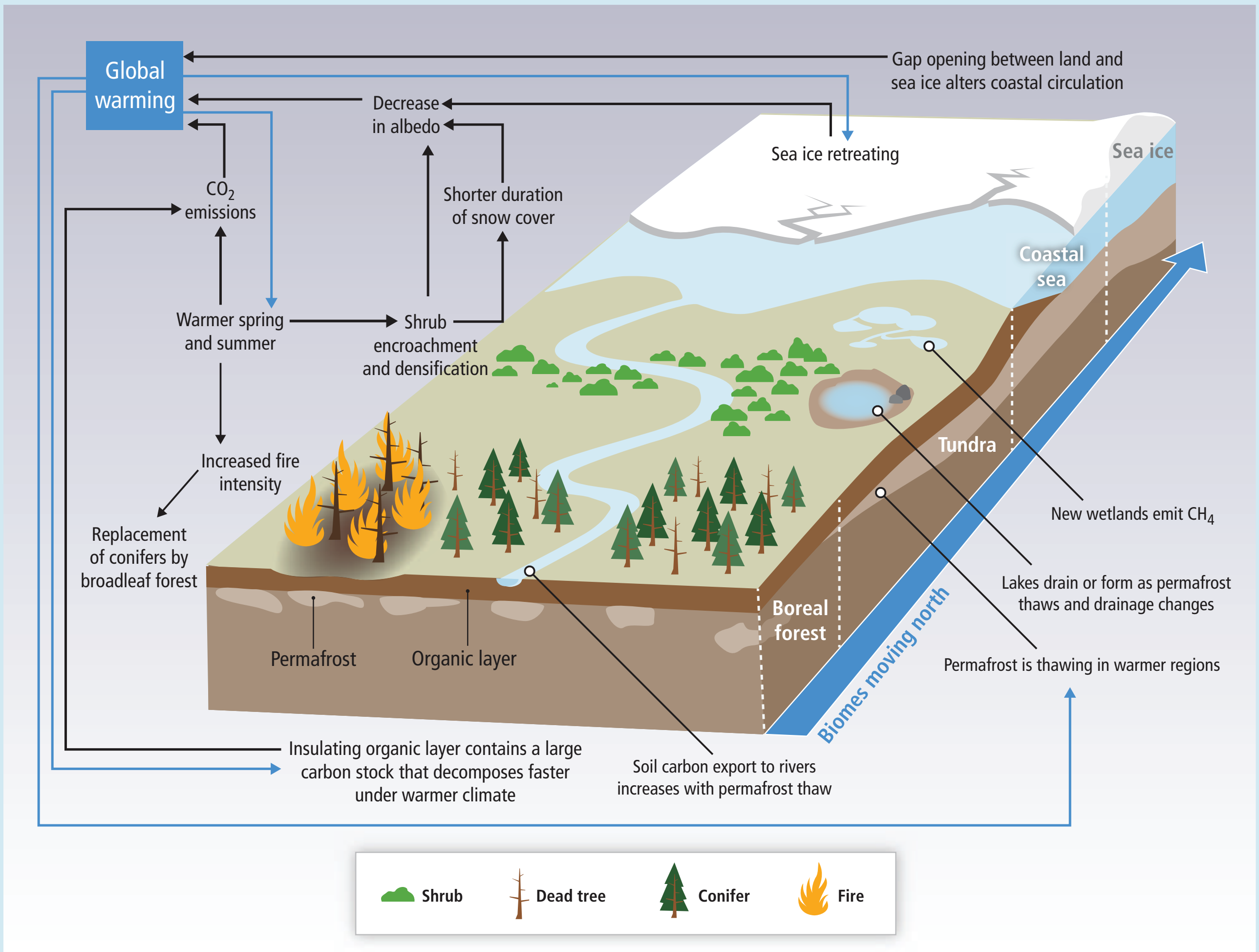

Figure 4-10 | Tundra–boreal biome shift. Earth System Models predict a northward shift of Arctic vegetation with climate warming, as the boreal biome migrates into what is currently tundra. Observations of shrub expansion in tundra, increased tree growth at the tundra–forest transition, and tree mortality at the southern extent of the boreal forest in recent decades are consistent with model projections. Vegetation changes associated with a biome shift, which is facilitated by intensification of the fire regime, will modify surface energy budgets, and net ecosystem carbon balance, permafrost thawing, and methane emissions, with net feedbacks to additional climate change.

Continued next page →

Box 4-4 (continued)

Gradual changes in composition resulting from decreased evergreen conifer productivity and increased mortality, as well as increased deciduous species productivity, can be facilitated by more rapid shifts associated with fire disturbance where it can occur (Mack et al., 2008; Johnstone et al., 2010; Roland et al., 2013). Each of these interacting processes, as well as insect disturbance and associated tree mortality, are tightly coupled with warming-induced drought (Choat et al., 2012; Ma et al., 2012; Anderegg et al., 2013a). Similarly, gradual productivity increases at the boreal-tundra ecotone are facilitated by long distance dispersal into areas disturbed by tundra fire and thermokarsting (Tchebakova et al., 2009; Brown, 2010; Hampe, 2011). In North America these coupled interactions set the stage for changes in ecological processes, already documented, consistent with a biome shift characterized by increased deciduous composition in the interior boreal forest and evergreen conifer migration into tundra areas that are, at the same time, experiencing increased shrub densification. The net feedback of these ecological changes to climate is multi-faceted, complex, and not yet well known across large regions except via modeling studies, which are often poorly constrained by observations.

as a positive feedback accelerating high-latitude warming (Chapin III et al., 2005; Bonfils et al., 2012).

There is *medium confidence* that rapid change in the Arctic is affecting its animals. For example, seven of 19 sub-populations of the polar bear are declining in number, while four are stable, one is increasing, and the remaining seven have insufficient data to identify a trend (Vongraven and Richardson, 2011). Declines of two of the sub-populations are linked to reductions in sea ice (Vongraven and Richardson, 2011). Polar bear populations are projected to decline greatly in response to continued Arctic warming (Hunter et al., 2010; Stirling and Derocher, 2012), and it is expected that the populations of other Arctic animals will be affected dramatically by climate change, often in complex but potentially dramatic ways (e.g., Post et al., 2009; Sharma et al., 2009; Gallant et al., 2012; Gilg et al., 2012; Post and Brodie, 2012; Gauthier et al., 2013; Nielsen and Wall, 2013; Prost et al., 2013; White et al., 2013). Simple niche-based or climatic envelope models have difficulty in capturing the full complexity of these future changes (MacDonald, 2010).

There is *high confidence* that alpine systems are already showing a high sensitivity to ongoing climate change and will be highly vulnerable to change in the future. In western North America, warming, glacier retreat, snowpack decline, and drying of soils are already causing a large increase in mountain forest mortality and wildfire, plus other ecosystem impacts (e.g., Westerling et al., 2006; Crimmins et al., 2009; van Mantgem et al., 2009; Pederson et al., 2010; Muhlfeld et al., 2011; Brusca et al., 2013; Williams et al., 2013), and disturbance will continue to be an important agent of climate-induced change in this region (Littell et al., 2010). Globally, tree line altitude appears to be changing, although not always in simple ways (Harsch et al., 2009; Tingley et al., 2012) and may sometimes be due to factors not related to climate change. Responses to climate change in high-altitude ecosystems are taking place in Africa, Asia, Europe, and elsewhere (Cannone et al., 2007, 2008; Yasuda et al., 2007; Lenoir et al., 2008, 2010; Britton et al., 2009; Chen et al., 2009, 2011; Cui and Graf, 2009; Normand et al., 2009; Allen, C.D. et al., 2010; Eggermont et al., 2010; Engler et al., 2011; Kudo et al., 2011; Laurance et al., 2011; Dullinger et al., 2012). For example, in a study of permanent plots from 1994 to 2004 in the Austrian high Alps, a range contraction of subnival to nival plant species was indicated at the downslope edge, and an expansion of alpine pioneer species at the upslope edge (Pauli et al., 2007). Thermophilous vascular plant species were observed to colonize in alpine mountain-top vegetation across Europe during the past decade (Gottfried et al., 2012). As with the Arctic, permafrost thawing in alpine systems could provide a strong positive feedback (e.g., Tibet; Cui and Graf, 2009).

4.3.3.5. Highly Human-Modified Systems

About a quarter of the land surface is now occupied by ecosystems highly modified by human activities. In this section we assess the vulnerability to climate change only of those modified systems not dealt with elsewhere, that is, excluding agriculture (Chapter 7), freshwater fisheries (Chapter 3), and urban areas (Chapter 8).

4.3.3.5.1. Plantation forestry

Plantation forests are established through afforestation or reforestation, often with tree crop replacement (Dohrenbusch and Bolte, 2007; FAO, 2010). They differ from natural or semi-natural forests (Section 4.3.3.1) by generally being even-aged, having a reduced species diversity (sometimes of non-native species), and being dedicated to the production of timber, pulp, and/or bioenergy. Plantation forests contribute 7% to the global forest area (FAO, 2010), an increase of 5 million hectares between 2000 and 2010 (FAO, 2010). Most recent plantations have been established by afforestation of non-forest areas in the tropics and subtropics and some temperate regions, particularly China (Kirilenko and Sedjo, 2007; FAO, 2010). Afforestation usually results in net CO_2 uptake from the atmosphere (Canadell and Raupach, 2008; Van Minnen et al., 2008) but does not necessarily result in a reduction in global warming (Bala et al., 2007; see Section 4.3.4.5).

Growth rates in plantation forests have generally increased during the last decades but the variability is large. In forests that are not highly water limited, increased growth is consistent with higher temperatures and extended growing seasons. As in the case of forests in general, clear attribution is difficult because of the interaction of multiple environmental drivers as well as changes in forest management (e.g., Boisvenue and Running, 2006; Ciais et al., 2008; Dale et al., 2010; see also Section 4.3.3.1). In Europe much of the increase has been attributed to recovery following previously more intense harvesting (Ciais et al., 2008; Lindner et al., 2010).

Several studies using forest yield models suggest future increases in forest production (Kirilenko and Sedjo, 2007). These results may overestimate the positive effects of elevated CO_2 (Kirilenko and Sedjo, 2007; see Section 4.2.4.4). The effects of disturbances such as wildfires, forest pests, pathogens, and windstorms, which are major drivers of forest dynamics, are poorly represented in the models (Loustau, 2010; see also Section 4.3.3.1 and Box 4-2). The results from different models often differ substantially both regarding forest productivity (e.g., Sitch et al., 2008; Keenan et al., 2011) and potential species ranges (see Section 4.3.3.1.2). Decreased forest production is expected in already dry forest regions for which further drying is projected, such as the southwestern USA (Williams, A.P. et al., 2010). Extreme drying may also decrease yields in forests currently not water limited (e.g., Sitch et al., 2008; see Section 4.3.3.1). Plantations in cold-limited areas could benefit from global warming, provided that increased fires, storms, pests, and pathogens do not outweigh the potential direct climate effects on tree growth rates.

Low species diversity (and low genetic diversity within species where clones or selected provenances are used) renders plantation forests less resilient to climate change than natural forests (e.g., Hemery, 2008). Choosing provenances that are well adapted to current climates but pre-adapted to future climates is difficult because of uncertainties in climate projections at the time scale of a plantation forest rotation (Broadmeadow et al., 2005). How forest pests and pathogens will spread as a result of climate change and other factors is highly uncertain. New pathogen-tree interactions may arise (e.g., Brasier and Webber, 2010). Adaptive management can decrease the vulnerability of plantation forests to climate change (Hemery, 2008; Bolte et al., 2009; Seppälä, 2009; Dale et al., 2010). For example, risk spreading by promoting mixed stands, containing multiple species or provenances, combined with natural regeneration (Kramer et al., 2010), has been advocated as an adaptation strategy for temperate forests (Hemery, 2008; Bolte et al., 2010) and tropical forests (Erskine et al., 2006; Petit and Montagnini, 2006). Incomplete knowledge of the ecology of tropical tree species and little experience in managing mixed tropical tree plantations remains a problem (Hall et al., 2011). Especially at the equator-ward limits of cold-adapted species, such as Norway spruce (*Picea abies*) in Europe, climate change will *very likely* lead to a shift in the main tree species used for forest plantations (Iverson et al., 2008; Bolte et al., 2010).

4.3.3.5.2. Bioenergy systems

The production of modern bioenergy is growing rapidly throughout the world in response to climate mitigation and energy security policies (Kirilenko and Sedjo, 2007). WGIII AR5 Chapter 7 addresses the potential of bioenergy as a climate mitigation strategy. The vulnerability of bioenergy systems to climate change is similar to that of plantation forestry (Section 4.3.3.5.1) or food crops (Section 7.3): in summary, they remain viable in the future in most but not all locations, but their viability is increasingly uncertain for high levels of climate change (Haberl et al., 2011). Oliver, R.J. et al. (2009) suggested that rising CO_2 might contribute to increased drought tolerance in bioenergy crops (because it leads to improved plant water use efficiency).

The unintended consequences of large-scale land use changes driven by increasing bioenergy demand are addressed in Section 4.4.4.

4.3.3.5.3. Cultural landscapes

Cultural landscapes are characterized by a long history of human-nature interactions, which results in a particular configuration of species and landscape pattern attaining high cultural significance (Rössler, 2006). Examples are grassland or mixed agriculture landscapes in Europe, rice landscapes in Asia (Kuldna et al., 2009), and many others across the globe (e.g., Rössler, 2006; Heckenberger et al., 2007). Such landscapes are often agricultural, but we deal with them here because their perceived value is only partly in terms of their agricultural products.

It has been suggested that protected area networks (such as Natura 2000 in Europe, which includes many cultural landscape elements) be adjusted to take into account climate change (Bertzky et al., 2010). Conserving species in cultural landscapes (e.g., EU Council, 1992) generally depends on maintaining certain types of land use. Doing so under climate change requires profound knowledge of the systems and species involved, and conservation success so far has been limited (see Thomas et al., 2009, for a notable exception). Understanding the relative importance of climate change and land management change is critical (Settele and Kühn, 2009). To date land use changes have been the most obvious driver of change (Nowicki et al., 2007); impacts have been attributed to climate change (with *low* to *medium confidence*) in only a few examples (Devictor et al., 2012). Even in these, combined land use-climate effects explain the pattern of observed threats better than either alone (Schweiger et al., 2008, 2012; Clavero et al., 2011).

There is *very high confidence* that species composition and landscape structure are changing in cultural landscapes such as Satoyama landscapes in Japan or mixed forest, agricultural landscapes in Europe. Models and experiments suggest that climate change should be contributing to these observed changes. The land use and land management signal is so strong in these landscapes that there is *very low confidence* that we can attribute these observations to climate change (Figure 4-4).

4.3.3.5.4. Urban ecosystems

Although urban areas (for definition see Section 8.1.2) cover only 0.5% of the Earth's land surface (Schneider et al., 2009), more than half of humanity lives there (increasing annually by 74 million people; UN DESA Population Division, 2012) and they harbor a large variety of species (McKinney, 2008). The frequency and magnitude of warm days and nights (heat waves) is *virtually certain* to increase globally in the future

Frequently Asked Questions

FAQ 4.5 | Why does it matter if ecosystems are altered by climate change?

Ecosystems provide essential services for all life: food, life-supporting atmospheric conditions, drinkable water, as well as raw materials for basic human needs such as clothing and housing. Ecosystems play a critical role in limiting the spread of human and non-human diseases. They have a strong impact on the weather and climate itself, which in turn impacts agriculture, food supplies, socioeconomic conditions, floods, and physical infrastructure. When ecosystems change, their capacity to supply these services changes as well—for better or worse. Human well-being is put at risk, along with the welfare of millions of other species. People have a strong emotional, spiritual, and ethical attachment to the ecosystems they know, and the species they contain.

By "ecosystem change" we mean changes in some or all of the following: the number and types of organisms present; the ecosystem's physical appearance (e.g., tall or short, open or dense vegetation); and the functioning of the system and all its interactive parts, including the cycling of nutrients and productivity. Though in the long term not all ecosystem changes are detrimental to all people or to all species, the faster and further ecosystems change in response to new climatic conditions, the more challenging it is for humans and other species to adapt to the new conditions.

(IPCC, 2012); this trend is higher in urban than in rural areas (McCarthy et al., 2010). Heavy rainfall events are also projected to increase (IPCC, 2012), and although the hydrological conditions in urban areas make them prone to flooding (*medium confidence*), there is *limited evidence* that they will be over-proportionally affected. It is very likely that sea level rise in the future will contribute to flooding, erosion, and salinization of coastal urban ecosystems (IPCC, 2012). Climate change is projected to increase the frequency of landslides (UN-HABITAT, 2011). Climate change impacts on urban ecosystems and biodiversity have received comparatively little attention, with water availability being an exception (Hunt and Watkiss, 2011). Changes in water availability and quality due to changes in precipitation, evaporation, or in salinity regimes will especially affect urban freshwater ecosystems (Hunt and Watkiss, 2011). As in other ecosystems, climate change will lead to a change in species composition, the frequency of traits, and ecosystem services from urban ecosystems. Knapp, S. et al. (2008) found that trait composition of plant communities changes during urbanization toward adaptive characteristics of dry and warm environments (see also Sections 4.2.4.6 and 4.3.2.5). Urban areas are one of the main points of introduction of alien species (e.g., for plants through urban gardening; Knapp, S. et al., 2012). Increased damage by phytophagous insects to plants in urban environments is anticipated (Kollár et al., 2009; Lopez-Vaamonde et al., 2010; Tubby and Webber, 2010; see also Section 8.2.4.5).

4.3.4. Impacts on Key Ecosystem Services

Ecosystem services are the benefits that people derive from ecosystems (see Glossary). Many ecosystem services are plausibly vulnerable to climate change. The Millennium Ecosystem Assessment classification (Millennium Ecosystem Assessment, 2003) recognizes *provisioning services* such as food (Chapter 7), fiber (Section 4.3.4.2), bioenergy (Section 4.3.4.3), and water (Chapter 3); *regulating services* such as climate regulation (Section 4.3.4.5), pollination, pest and disease control (Section 4.3.4.4), and flood control (Chapter 3); *supporting services* such as primary production (Section 4.3.2.2) and nutrient cycling (Section 4.2.4.2, and indirectly Section 4.3.2.3); and *cultural services*, including recreation and aesthetic and spiritual benefits (Section 10.6). Section 4.3.4.1 focuses on ecosystem services not already covered in the sections referenced above.

4.3.4.1. Habitat for Biodiversity

Climate change can alter habitat for species by inducing (1) shifts in habitat distribution that are not followed by species, (2) shifts in species distributions that move them outside of their preferred habitats, and (3) changes in habitat quality (Dullinger et al., 2012; Urban et al., 2012). Climate change impacts on habitats for biodiversity are already occurring (see the polar bear example in Section 28.2.2.1.3) but are not yet a widespread phenomenon. Models of future climate change-induced shifts in the distribution of ecosystems suggest that many species could be outside of their preferred habitats within the next few decades (Urban et al., 2012; see Sections 4.3.2.5, 4.3.3, and Figure 4-1).

Hole et al. (2009) report that the majority of African birds would have to move large distances (up to several hundred kilometers) over the next 60 years (under SRES B2a), resulting in substantial turnover of species within protected areas (>50% turnover in more than 40% of Important Bird Areas of Africa). To reach suitable climates they will have to migrate across unfavorable habitats. Many may continue to find suitable climate within the protected area network, but will be forced to cope with new habitat constraints (Hole et al., 2009). Araujo et al. (2011) estimate that by 2080 approximately 60% (58 ± 2.6%) of plants and vertebrate species will no longer have favorable climates within European protected areas, often pushing them into unsuitable or less preferred habitats (based on SRES A1, A2, B1, and A1FI scenarios). Wiens et al. (2011) project similar effects in the western USA (until the year 2069, based on SRES A2 scenarios), but also find that climate change may open up new opportunities for protecting species in areas where climate is currently unsuitable. In some cases climate change may allow species to move into areas of lower current or future land use pressure including protected areas (Bomhard et al., 2005). These studies strongly argue for a rethinking of protected areas networks and of the importance of the habitat matrix outside of protected areas as a key to migration and long-term survival of species (see Sections 4.4.2.2, 4.4.2.3).

In the long term, some habitat types may disappear entirely due to climate change (see Section 4.3.3 and Figure 4-1). Climates are projected to occur in the future that at least in some features do not represent climates that existed in the past (Williams, J.W. et al., 2007; Wiens et al., 2011), and in the past climate shifts have resulted in vegetation types that have no current analog (Section 4.2.3). The impacts of habitat change on species abundance and extinction risk are difficult to evaluate because at least some species are able to adapt to novel habitats (Prugh et al., 2008; Oliver, T. et al., 2009). The uncertainty in habitat specificity is one reason why quantitative projection of changes in extinction rates is difficult (Malcolm et al., 2006).

The effects of climate change on habitat quality are less well studied than shifts in species or habitat distributions. Several recent studies indicate that climate change may have altered habitat quality already and will continue to do so (Iverson et al., 2011; Matthews et al., 2011). For example, decreasing snowfall in the southwestern USA has negatively affected the habitat for songbirds (Martin and Maron, 2012).

4.3.4.2. Timber and Pulp Production

In most areas with forest plantations, forest growth rates have increased during the last decades, but the variability is large, and in some areas production has decreased (see Section 4.3.3.1). In forests that are not highly water limited, these trends are consistent with higher temperatures and extended growing seasons, but, as in the case of forests in general, clear attribution is difficult because many environmental drivers and changes in forest management interact (e.g., Boisvenue and Running, 2006; Ciais et al., 2008; Dale et al., 2010; see also Section 4.3.3.1). In Europe a reduction in harvesting intensity has contributed (Ciais et al., 2008; Lindner et al., 2010).

Forest yield models project future increases in forest production under climate change, perhaps over optimistically (Kirilenko and Sedjo, 2007; see Section 4.2.4.4). Using a model that accounts for fire effects and insect damage, Kurz et al. (2008) showed that the Canadian forest sector may have transitioned from a sink to a source of carbon.

4.3.4.3. Biomass-Derived Energy

Bioenergy sources include traditional forms such as wood and charcoal from forests (see Section 4.3.3.1) and more modern forms such as the industrial burning of biomass wastes, the production of ethanol and biodiesel, and plantations of bioenergy crops. While traditional biofuels have been in general decline as users switch to fossil fuels or electricity, they remain dominant energy sources in many less developed parts of the world, such as Africa, and retain a niche in developed countries. Generally, potentials of bioenergy production under climate change may be high, but are very uncertain (Haberl et al., 2011).

4.3.4.4. Pollination, Pest, and Disease Regulation

It can be inferred that global change will result in new communities (Gilman et al., 2010; Schweiger et al., 2010). As these will have had little opportunity for coevolution, changes in ecological interactions, such as shifts in herbivore diets, the range of prey of predators, or in pollination networks are to be expected (Tylianakis et al., 2008; Schweiger et al., 2012). This may result in temporarily reduced effectiveness of the "regulating services," which generally depend on species interactions (Montoya and Raffaelli, 2010). Burkle et al. (2013) show that the loss of species reduces co-occurrence of interacting species and thus reduces ecosystem functions based on them.

Climate change tends to increase the abundance of pest species, particularly in previously cooler climates, but assessments of changes in impacts are hard to make (Payette, 2007). Insect pests are directly influenced by climate change, for example, through a longer warm season during which to breed, and indirectly, for example, through the quality of food plants (Jamieson et al., 2012) or via changes in their natural enemies (predators and parasitoids). Insects have well-defined temperature optima; warming toward the optimum leads to increased vitality and reproduction (Allen, C.D. et al., 2010). Mild winters in temperate areas promote pests formerly controlled by frost sensitivity. For the vast majority of indirect effects, information is scarce. Further assessments of climate change effects on pest and disease dynamics are found in Sections 7.3.2.3 for agricultural pests and 11.5.1 for human diseases.

Climate change has severe negative impacts on pollinators (including honeybees) and pollination (Kjøhl et al., 2011) (*medium confidence*). After land use changes, climate change is regarded as the second most relevant factor responsible for the decline of pollinators (Potts et al., 2010; for other factors see Biesmeijer et al., 2006; Brittain et al., 2010a,b). The potential influence of climate change on pollination can be manifold (compare Hegland et al., 2009; Schweiger et al., 2010; Roberts et al., 2011). There are a few observational studies, which mostly relate to the phenological decoupling of plants and their pollinators (Gordo and Sanz, 2005; Bartomeus et al., 2011). While Willmer (2012) states, based on experimental studies, that phenological effects may be less important than has been suggested, an analysis of phenological observations in plants by Wolkovich et al. (2012) shows that experimental data on phenology may grossly underestimate the actual phenological shifts.

Le Conte and Navajas (2008) state that the generally observed decline in honeybees is a clear indication of an increasing susceptibility to global change phenomena, with pesticide application, new diseases, and stress (and a combination of these) as the most relevant causes. Climate change may contribute by modifying the balance between honeybees and their environment (including exposure or susceptibility to diseases). Honeybees show a high capacity to adjust to a variety of environments; their high genetic diversity should allow them to also cope with climatic change (Bartomeus et al., 2011). The preservation of genetic variability within honeybees is regarded as a key adaptation strategy for pollination services (Le Conte and Navajas, 2008).

4.3.4.5. Moderation of Climate Change, Variability, and Extremes

The focus of this section is on processes operating at regional to global scales, rather than the well-known microclimatic benefits of ecosystems in smoothing day-night temperature variations and providing local evaporative cooling. In the decade 2000–2009, the global net uptake of CO_2 by terrestrial ecosystems was a large fraction of the anthropogenic CO_2 emissions to the atmosphere from all sources, reducing the rate of climate change proportionately (Section 4.3.2.3; WGI AR5 Section 6.3.2).

Afforestation or reforestation are potential climate mitigation options (Van Minnen et al., 2008; Vaughan and Lenton, 2011; Fiorese and Guariso, 2013; Singh et al., 2013) but, as discussed in Section 4.2.4.1, the net effect of afforestation on the global climate is mixed and context dependent. Wickham et al. (2012) found significant positive correlations between the average annual surface temperature and the proportion of forest in the landscape and conclude that the climate benefit of temperate afforestation is unclear. Where low-albedo forest canopies replace higher-albedo surfaces such as soil, grassland, or snow, the resultant increase in net radiative forcing counteracts the benefits of carbon sequestration to some degree (Arora and Montenegro, 2011). Where the cloud cover fraction is low and the albedo difference is large, that is, outside the humid tropics, the long-term net result of afforestation can be global warming (Bala et al., 2007; Bathiany et al., 2010; Schwaiger and Bird, 2010). Accounting for changes in albedo and indirect greenhouse effects are not currently required in the formal rules for quantifying for the climate effects of land use activities (Schwaiger and Bird, 2010; Kirschbaum et al., 2012). There are potential negative trade-offs between afforestation for climate mitigation purposes and other ecosystem services, such as water supply (Jackson et al., 2005) and biodiversity maintenance (CBD, 2012; Russell et al., 2012).

It has been suggested (Ridgwell et al., 2009) that planting large areas of crop varieties with highly reflective leaves could help mitigate global change. Model analyses indicate this "geo-engineering" strategy would be marginally effective at high latitudes, but have undesirable climate consequences at low latitudes. Measurements of leaf albedo in major crops show that the current range of variability is insufficient to make a meaningful difference to the global climate (Doughty et al., 2011).

4.4. Adaptation and Its Limits

4.4.1. Autonomous Adaptation by Ecosystems and Wild Organisms

Autonomous adaptation (see Glossary under adaptation) refers to the adjustments made by ecosystems, including their human components, without external intervention, in response to a changing environment (Smit et al., 2000)—also called "spontaneous adaptation" (Smit et al., 2007). In the context of human systems it is sometimes called "coping capacity." The capacity for autonomous adaptation is part of resilience but is not exactly synonymous (Walker et al., 2004).

All social and ecological systems have some capacity for autonomous adaptation. Ecosystems that have persisted for a long time can reasonably be inferred to have a high capacity for autonomous adaptation, at least with respect to the variability that they have experienced in the past. An environmental change that is more rapid than in the past or is accompanied by other stresses may exceed the previously demonstrated adaptive capacity of the system. Adaptation at one level, for instance by organisms in a community, can confer greater resilience at higher organization levels, such as the ecosystem (Morecroft et al., 2012). The mechanisms of autonomous adaptation of organisms and ecosystems consist of changes in the physiology, behavior, phenology, or physical form of organisms, within the range permitted by their genes and the variety of genes in the population; changes in the genetic composition of the populations; and change in the composition of the community, through in- or out-migration or local extinction.

The ability to project impacts of climate change on ecosystems is complicated by the potential for species to adapt. Adaptation by individual species increases their ability to survive and flourish under different climatic conditions, possibly leading to lower risks of extinction than predicted from statistical correlations between current distribution and climate (Botkin et al., 2007). It may also affect their interactions with other species, leading to disruption of the biotic community (Visser and Both, 2005).

4.4.1.1. Phenological

Changes in phenology are occurring in many species and locations (Section 4.3.2.1). Further evidence since AR4 shows how this can be an adaptation to climate change, but also the limits to phenological adaptation. An organism's phenology is typically highly adapted to the climate seasonality of the environment in which it evolved. Species unable to adjust their phenological behavior will be negatively affected, particularly in highly seasonal habitats (Both et al., 2010).

Moreover, the phenology of any species also needs to be keyed to the phenology of other species with which it interacts, such as competitors, food species, and pollinators. Systematic cross-taxa studies indicate different rates of phenological change for different species and trophic levels (Parmesan, 2007; Cook et al., 2008; Thackeray et al., 2010). If adaptation is insufficiently rapid or coordinated between interdependent species, disruption of ecological features such as trophic cascades, competitive hierarchies, and species coexistence is inferred to result (Nakazawa and Doi, 2012). Lack of coordination can occur if one of the species is cued to environmental signals that are not affected by climate change, such as day length (Parmesan, 2006). Increasing temperatures may bring species either more into or out of synchrony, depending on their respective starting positions (Singer and Parmesan, 2010), although evidence is more toward a loss of synchrony (Thackeray et al., 2010).

Changes in interspecific interactions, such as predator-prey or interspecific competition for food, stemming from changes in phenological characteristics and breakdown in synchrony between species have been observed. For example, bird breeding is most effective when synchronized with the availability of food, so changes in the phenology of food supplies can exert a selective pressure on birds. In a study of 100

European migratory bird species, those that advanced their arrival date showed stable or increasing populations between 1990 and 2000, while those that did not adjust their arrival date on average showed declining populations (Møller et al., 2008). In a comparison of nine Dutch populations of the migratory pied flycatcher (*Ficedula hypoleuca*) between 1987 and 2003, populations declined by 90% in areas where food peaked early in the season and the arrival of the birds was mis-timed, but not in areas with a later food peak that could still be exploited by early breeding birds (Both et al., 2006). However, compensating processes can exist: for example, in a 4-decade study of great tits (*Parus major*), breeding populations were buffered against phenological mismatch due to relaxed competition between individual fledglings (Reed et al., 2013). Between 1970 and 1990, changes in migration date did not predict changes in population sizes (Møller et al., 2008).

Bird breeding can also be affected by phenological shifts in competing species and predators. Between 1953 and 2005 in southwestern Finland, the onset of breeding of the resident great tit *Parus major* and the migratory pied flycatcher (*Ficedula hypoleuca*) became closer to each other, increasing competition between them (Ahola et al., 2007). The edible dormouse (*Glis glis*), a nest predator, advanced its hibernation termination by -8 days per decade in the Czech Republic between 1980 and 2005 due to increasing annual spring air temperatures, leading to increased nest predation in three out of four surveyed bird species (Adamik and Kral, 2008).

Plant-insect interactions have also been observed to change. In Illinois, USA, the pattern of which plants were pollinated by which bees were altered by differing rates of phenological shifts and landscape changes over 120 years, with 50% of bee species becoming locally extinct (Burkle et al., 2013). Increasing asynchrony of the winter moth (*Operophtera brumata*) and its feeding host oak tree (*Quercus robur*) in the Netherlands was linked to increasing spring temperatures but unchanging winter temperatures (van Asch and Visser, 2007). Warmer temperatures shorten the development period of European pine sawfly larvae (*Neodiprion sertifer*), reducing the risk of predation and potentially increasing the risk of insect outbreaks, but interactions with other factors including day length and food quality may complicate this prediction (Kollberg et al., 2013). In North America, the spruce budworm (*Choristaneura fumiferana*) lays eggs with a wide range of emergence timings, so the population as a whole is less sensitive to changing phenology of host trees (Volney and Fleming, 2007).

The environmental cues for phenological events are complex and multi-layered (Körner and Basler, 2010; Singer and Parmesan, 2010). For instance, many late-succession temperate trees require a chilling period in winter, followed by a threshold in day length, and only then are sensitive to temperature. As a result, simple projections of current phenological trends may be misleading, since the relative importance of cues can change (Cook et al., 2012b). The effects are complex and sometimes apparently counterintuitive, such as the increased sensitivity of flowering in high-altitude perennial herbs in the Rocky Mountains to frost because plants begin flowering earlier as a result of earlier snowmelt (Inouye, 2008).

It has been suggested that shorter generation times give greater opportunity for autonomous adaptation through natural selection (Rosenheim and Tabashnik, 1991; Bertaux et al., 2004), but a standardized assessment of 25,532 rates of phenological change for 726 UK taxa indicated that generation time had only limited influence on adaptation rates (Thackeray et al., 2010).

There is *high confidence* (*much evidence*, *medium agreement*) that climate change-induced phenological shifts will continue to alter the interactions between species in regions with a marked seasonal cycle.

4.4.1.2. Evolutionary and Genetic

Since AR4 there has been substantial progress in defining the concepts and tools necessary for documenting and predicting evolutionary and genetic responses to recent and future climate change, often referred to as "rapid evolution." Evolution can occur through many mechanisms, including selection of existing genes or genotypes within populations, hybridization, mutation, and selection of new adaptive genes and perhaps even through epigenetics (Chevin et al., 2010; Chown et al., 2010; Lavergne et al., 2010; Paun et al., 2010; Hoffmann and Sgro, 2011; Anderson et al., 2012a; Donnelly et al., 2012; Franks and Hoffmann, 2012; Hegarty, 2012; Merilä, 2012; Bell, 2013; Zhang et al., 2013). Mechanisms such as selection of existing genes and genotypes, hybridization, and epigenetics can lead to adaptation in very few generations, while others, notably mutation and selection of new genes, typically take many tens of generations. This means that species with very fast life cycles, for example, bacteria, should in general have greater capacity to respond to climate change than species with long life cycles, such as large mammals and trees. There is a paucity of observational or experimental data that can be used for detection and attribution of recent climate effects on evolution.

4.4.1.2.1. Observed evolutionary and genetic responses to rapid changes in climate

There is a small but growing body of observations supporting the AR4 assessment that some species may have adapted to recent climate warming or to climatic extremes through genetic responses (e.g., plants: Franks and Weis, 2008; Hill et al., 2011; Anderson et al., 2012b; vertebrates: Ozgul et al., 2010; Phillimore et al., 2010; Husby et al., 2011; Karell et al., 2011; insects: Buckley et al., 2012; van Asch et al., 2012). Karell et al. (2011) found increasing numbers of brown genotypes of the tawny owl (*Strix aluco*) in Finland over the course of the last 28 years and attributed it to fewer snow-rich winters, which creates strong selection pressure against the white genotype. Earlier spawning by the common frog (*Rana temporaria*) in Britain could be attributed largely to local genetic adaptation to increasing spring temperatures (Phillimore et al., 2010). Using a combination of models and observations, Husby et al. (2011) have built a case for detection and attribution of genetic adaptation in an insectivorous bird and in an herbivorous insect that has tracked warming-related changes in the budburst timing of its host tree (van Asch et al., 2012). In contrast, many species appear to be maladapted to changing climates, in part because factors such as limited existing genetic variation, weak heritability of adaptive traits, or conflicting constraints on adaptation create low potential for rapid evolution (Knudsen et al., 2011; Ketola et al., 2012; Merilä, 2012; Mihoub et al., 2012). Most studies of rapid evolution suffer from methodological

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weaknesses, making it difficult to demonstrate clearly a genetic basis underlying observed phenotypic responses to environmental change (Gienapp et al., 2008; Franks and Hoffmann, 2012; Hansen et al., 2012; Merilä, 2012). Rapid advances in quantitative genetics, genomics, and phylogenetics, combined with recent progress on conceptual frameworks, will substantially improve the detection and attribution of genetic responses to changing climate over the next few years (Davis, C.C. et al., 2010; Salamin et al., 2010; Hoffmann and Sgro, 2011). In sum, there are few observational studies of rapid evolution and difficulties in detection and attribution, so there is only *medium confidence* that some species have responded to recent changes in climate through genetic adaptations, and insufficient evidence to determine if this is a widespread phenomenon (thus *low confidence* for detection and attribution across all species; Figure 4-4).

The ability of species to adapt to new environmental conditions through rapid evolutionary processes can also be inferred from the degree to which environmental niches are conserved when environment is changed. There is evidence that environmental niches are conserved for some species under some conditions (plants: Petitpierre et al., 2012; birds: Monahan and Tingley, 2012; review: Peterson et al., 2011), but also evidence suggesting that environmental niches can evolve over time scales of several decades following changes in climate (Broennimann et al., 2007; Angetter et al., 2011; Konarzewski et al., 2012; Leal and Gunderson, 2012; Lavergne et al., 2013). The paleontological record provides insight into evolutionary responses in the face of natural climate variation. In general, environmental niches appear to be broadly conserved through time although there are insufficient data to determine the extent to which genetic adaptation has attenuated range shifts and changes in population size (Peterson et al., 2011; Willis and MacDonald, 2011). Phylogeographic reconstructions of past species distributions suggest that hybridization may have helped avoid extinctions during cycles of glaciation and could also play a key role in future adaptation (Hegarty, 2012; Soliani et al., 2012). There is new evidence that epigenetic mechanisms, such as DNA methylation, could allow very rapid adaptation to climate (Paun et al., 2010; Zhang et al., 2013).

4.4.1.2.2. Mechanisms mediating rapid evolutionary response to future climate change

Studies of genetic variability across species ranges, and models that couple gene flow with spatially explicit population dynamics, suggest counterintuitive responses to climate change. Too much or too little gene flow to populations at range margins can create fragile, maladapted populations, which is in contrast to the current wisdom that populations at the range margins may be best adapted to global warming (Bridle et al., 2010; Hill et al., 2011). Conversely, there is evidence from experiments, models, and observations that populations in the center of species ranges may in some cases be more sensitive to environmental change than those at range boundaries (Bell and Gonzalez, 2009). Generalization is complicated by the interactions between local adaptation, gene flow, population dynamics, and species interactions (Bridle et al., 2010; Norberg et al., 2012).

Substantial progress has been made since AR4 in developing models for exploring whether genetic adaptation is fast enough to track climate change. Models of long-lived tree species suggest that existing genetic variation may be sufficient to slightly attenuate negative impacts of future climate change (Kuparinen et al., 2010; Kremer et al., 2012). However, these studies also indicate that adaptive responses will lag far behind even modest rates of projected climate change, owing to the very long generation time of trees. In a species with much shorter generation times, the great tit (*Parus major*), Gienapp et al. (2013) found that modeled avian breeding times tracked climate change, only at low to moderate rates of change. For a herbivorous insect with an even faster life cycle, van Asch et al. (2007, 2012) predicted that rapid evolution of the phenological response should have allowed it to track recent warming, which it has.

More broadly, models suggest that species with short generation times (1 year or less) potentially have the capacity to genetically adapt to even the most rapid rates of projected climate change given large enough present-day populations, but species with longer generation times or small populations could be at risk of extinction at moderate to high rates of climate change (Walters et al., 2012; Vedder et al., 2013). Recent experimental and theoretical work on "evolutionary rescue" shows that long-term avoidance of extinction through genetic adaptation to hostile environments is possible, but requires large initial genetic variation and population sizes and is accompanied by substantial loss of genetic diversity, reductions in population size, and range contractions over many generations before population recovery (Bell, 2013; Schiffers et al., 2013).

Model-based projections must be viewed with considerable caution because there are many evolutionary and ecological mechanisms not accounted for in most models that can either speed up or inhibit heritable adaptation to climate change (Cobben et al., 2012; Norberg et al., 2012; Kovach-Orr and Fussmann, 2013). In some cases, accounting for evolutionary processes in models even leads to predictions of greater maladaptation to climate change, resulting in rapid population declines (Hendry and Gonzalez, 2008; Ferriere and Legendre, 2013). Phenotypic plasticity is thought to generally improve the odds of adaptation to climate change. High plasticity in the face of climate change that has low fitness costs can greatly improve the odds of adaptation; however, plasticity with high costs leads to only modest amounts of adaptation (Chevin et al., 2010).

AR4 concluded that "projected rates of climate change are *very likely* to exceed rates of evolutionary adaptation in many species (*high confidence*)" (Fischlin et al., 2007). Work since then provides a similar, but more nuanced view of rapid evolution in the face of future climate change. The lack of adaptation in some species to recent changes in climate, broad support for niche conservatism, and models showing limited adaptive capacity in species with long generation times all indicate that high rates of climate change (RCP8.5) will exceed the adaptive capacities of many species (*high confidence*). On the other hand, evidence from observations and models also indicates that there is substantial capacity for genetic adaptation to attenuate phenological shifts, population declines, and local extinctions in many species, especially for low rates of climate change (RCP2.6) (*high confidence*). Projected adaptation to climate change is frequently characterized by population declines and loss of genetic diversity for many generations (*medium confidence*), thereby increasing species vulnerability to other pressures.

4.4.1.3. Migration of Species

This mode of adaptation has been extensively dealt with in Section 4.3.2.5. It is anticipated that the observed movement of species—individually and collectively—will continue in response to shifting climate patterns. Its effectiveness as an adaptation mechanism is constrained by three factors. First, the rate of migration for many species, in many regions of the world, is slower than the rate of movement of the climate envelope (see Figure 4-5). Second, the ecosystem interactions can remain intact only if all parts of the ecosystem migrate simultaneously and at the same rate. Third, the contemporary landscape and inland water systems contain many barriers to migration, in the form of habitat fragmentation, roads, human settlements, and dams. Mountain ecosystems are less constrained by these factors than flat-land ecosystems, but have additional impediments for species already close to the top of the mountain.

4.4.2. Human-Assisted Adaptation

Human-assisted adaptation means a deliberate intervention with the intent of increasing the capacity of the target organism, ecosystem, or socio-ecological system to survive and function at an acceptable level in the presence of climate change. It is also known as "planned adaptation" (Smit et al., 2007). This chapter focuses less on the adaptation of people, human communities, and infrastructure, as they are the topics of Chapters 8 to 17, and more on non-human organisms and ecosystems, while acknowledging the importance of the human elements within the ecosystem. Intervention in this context means a range of actions, including ensuring the presence of suitable habitat and dispersal pathways; reducing non-climate stressors; and physically moving organisms and storing and establishing them in new places. In addition to the other approaches assessed in this section, "Ecosystem-Based Adaptation" (see Box CC-EA) provides an option that integrates the use of biodiversity and ecosystem services into climate change adaptation strategies in ways that can optimize co-benefits for local communities and carbon management, as well as reduce the risks associated with possible maladaptation. Note that there are risks associated with all forms of human-assisted adaptation (see Section 4.4.4), particularly in the presence of far-from-perfect predictive capabilities (Willis and Bhagwat, 2009).

4.4.2.1. Reduction of Non-Climate Stresses and Restoration of Degraded Ecosystems

The alleviation of other stresses acting on ecosystems is suggested to increase the capacity of ecosystems to survive, and adapt to, climate change, as the effects are generally either additive or compounding. Ecosystem restoration is one way of alleviating such stresses while increasing the area available for adaptation (Harris et al., 2006). Building the resilience of at-risk ecosystems by identifying the full set of drivers of change and most important areas and resources for protection is the core of the adaptation strategy for the Arctic (Christie and Sommerkorn, 2012). Protective and restorative actions aimed at increasing resilience can also be a cost-effective means as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change and may have other social, economic, and cultural benefits. This is part of "ecosystem-based adaptation" (Colls et al., 2009; Box CC-EA).

4.4.2.2. The Size, Location, and Layout of Protected Areas

Additions to, or reconfigurations of, the protected area estate are commonly suggested as pre-adaptations to projected climate changes (Heller and Zavaleta, 2009). This is because for most protected areas, under plausible scenarios of climate change, a significant fraction of the biota will no longer have a viable population within the present protected area footprint. It is noted that the extant geography of protected areas is far from optimal for biodiversity protection even under the current climate; that most biodiversity exists outside rather than in protected areas and this between-protected area matrix is as important; that it is usually cheaper to acquire land proactively in the areas of projected future bioclimatic suitability than to correct the current non-optimality and then later add on areas to deal with climate change as it unfolds (Hannah et al., 2007); and that the existing protected area network will still have utility in future climates, even though it may contain different species (Thomas et al., 2012).

Hickler et al. (2012) analyzed the layout of protected areas in Europe and concluded that under projected 21st century climate change a third to a half of them would potentially be occupied by different vegetation than they currently represent. The new areas that need to be added to the existing protected area network to ensure future representativeness is situation specific, but some general design rules apply: orientation along climate gradients (e.g., altitudinal gradients) is more effective than orientation across them (Roux et al., 2008); regional scale planning is more effective than treating each local case independently because it is the network of habitats and protected areas that confers resilience rather than any single element (Heller and Zavaleta, 2009); and better integration of protected areas with a biodiversity-hospitable landscape outside is more effective than treating the protected areas as islands (Willis and Bhagwat, 2009). Dunlop et al. (2012) assessed the implications of climate change for biodiversity conservation in Australia and found many opportunities to facilitate the natural adaptation of biodiversity, including expanding the network of protected areas and restoring habitat at a large scale.

4.4.2.3. Landscape and Watershed Management

The need to include climate change into the management of vulnerable ecosystems is explicitly included in the strategic goals of the Convention on Biological Diversity. Oliver et al. (2012b) developed decision trees based on three scenarios: (1) *adversely sensitive*, where areas within the species current geographical range will become climatically unsuitable with a changing climate; (2) *climate overlap*, where there are areas that should remain climatically suitable within the species' range; and (3) *new climatic space*, which refers to areas outside of the current range that are projected to become suitable. Heller and Zavaleta (2009) reviewed recommendations in the published literature and argue that the majority of them, such as increase habitat heterogeneity of sites and connectivity of habitats across landscapes, lack sufficient specificity to ensure the persistence of many species and related ecosystem services to ongoing climate change. To date, recommendations are overwhelmingly focused on ecological data, neglecting social science insights. Few resources or capacity exist to guide adaptation planning processes at any scale.

Frequently Asked Questions

FAQ 4.6 | Can ecosystems be managed to help them and people to adapt to climate change?

The ability of human societies to adapt to climate change will depend, in large measure, on the management of terrestrial and inland freshwater ecosystems. A fifth of global human-caused carbon emissions today are absorbed by terrestrial ecosystems; this important carbon sink operates largely without human intervention, but could be increased through a concerted effort to reduce forest loss and to restore damaged ecosystems, which also co-benefits the conservation of biodiversity.

The clearing and degradation of forests and peatlands represents a source of carbon emissions to the atmosphere which can be reduced through management; for instance, there has been a three-quarters decline in the rate of deforestation in the Brazilian Amazon in the last 2 decades. Adaptation is also helped through more proactive detection and management of wildfire and pest outbreaks, reduced drainage of peatlands, the creation of species migration corridors, and assisted migration.

Climate-induced impacts to hydrological and thermal regimes in freshwater systems can be offset through improved management of environmental flow releases from reservoirs (Arthington et al., 2006, 2010 and references therein; Poff et al., 2010). Protection and restoration of riparian vegetation in small stream systems provide an effective strategy to moderate temperature regimes and offset warming, and protect water quality for downstream ecosystems and water supply areas (Davies, 2010; Capon et al., 2013).

General principles for management adaptations were summarized from a major literature review by West et al. (2009). They suggest that in the context of climate change, successful management of natural resources will require cycling between "managing for resilience" and "managing for change." This requires the anticipation of changes that can alter the impacts of grazing, fire, logging, harvesting, recreation, and so on. At the national level, principles to facilitate adaptation include (1) management at appropriate scales, and not necessarily the scales of convenience or tradition; (2) increased collaboration among agencies; (3) rational approaches for establishing priorities and applying triage; and (4) management with the expectation of ecosystem change, rather than keeping them as they have been. Barriers and opportunities were divided into four categories: (1) legislation and regulations, (2) management policies and procedures, (3) human and financial capital, and (4) information and science.

Steenberg et al. (2011) simulated the effect on adaptive capacity of three variables related to timber harvesting: the canopy-opening size of harvests, the age of harvested trees within a stand, and the species composition of harvested trees within a stand. The combination of all three adaptation treatments allowed target species and old forest to remain reasonably well represented without diminishing the timber supply. This minimized the trade-offs between management values and climate adaptation objectives. Manipulation of vegetation composition and stand structure has been proposed as a strategy for offsetting climatic change impacts on wildfires in Canada. Large areas of boreal forests are currently being harvested and there may be opportunities for using planned manipulation of vegetation for management of future wildfire risks. This management option could also provide an additional benefit to the use of assisted species migration because the latter would require introducing non-flammable broadleaves species into forests that are otherwise highly flammable (Girardin et al., 2013b; Terrier et al., 2013). Harvesting practices, such as partial cuts that limit the opening of the forest cover created by harvest, will be a key element to maintain diverse forest compositions and age class distributions in boreal forests. Another sound option for decreasing the exposure of silvicultural investments to an increasing fire danger is to use tree species requiring a shorter rotation (Girardin et al., 2013a).

4.4.2.4. Assisted Migration

Assisted migration has been proposed when fragmentation of habitats limits migration potential or when natural migration rates are outstripped by the pace of climate change (Hoegh-Guldberg et al., 2008; Vitt et al., 2010; Chmura et al., 2011; Loss et al., 2011; Ste-Marie et al., 2011). The options for management can be summarized as: (1) try to maintain or improve existing habitat or environment so that species do not have to move (e.g., Settele and Kühn, 2009); (2) maintain or improve migration corridors, including active management to improve survival along the moving margin of the distribution (Lawson et al., 2012); and (3) directly translocate species or genetically distinct populations within a species (Aitken et al., 2008; Hoegh-Guldberg et al., 2008; Rehfeldt and Jaquish, 2010; Loss et al., 2011; Pedlar et al., 2012). There is *low agreement* whether it is better to increase the resilience to climate change of ecosystems as they currently occur, or to enhance capacity of ecosystems to transform in the face of climate change (Richardson et al., 2009).

There is *high agreement* that maintaining or improving migration corridors or ecological networks is a low-regret strategy, partly because it is also seen as useful in combatting the negative effects of habitat fragmentation on population dynamics (Hole et al., 2011; Jongman et al., 2011). This approach has the benefit of improving the migration potential for large numbers of species and is therefore a more ecosystem-wide approach than assisted migration for individual species. However, observational and modeling studies show that increases in habitat connectivity do not always improve the population dynamics of target species, may decrease species diversity, and may also facilitate the spread of invasive species (Cadotte, 2006; Brisson et al., 2010; Matthiessen et al., 2010).

There is *medium agreement* that the practice of assisted migration of targeted species is a useful adaptation option (Hoegh-Guldberg et al., 2008; Vitt et al., 2009; Willis and Bhagwat, 2009; Loss et al., 2011; Hewitt et al., 2011). The velocity of 21st century climate change and substantial habitat fragmentation in large parts of the world means that many species will be unable to migrate or adapt fast enough to keep pace with climate change (Figure 4-5), posing problems for long-term survival of the species. Some ecologists believe that careful selection of species to be moved would minimize the risk of undesirable impacts on existing communities or ecosystem function (Minteer and Collins, 2010), but others argue that the history of intentional species introductions shows that the outcomes are unpredictable and in many cases have had disastrous impacts (Ricciardi and Simberloff, 2009). The number of species that require assisted migration could easily overwhelm funding capacity (Minteer and Collins, 2010). Decisions regarding which species should be translocated are complex and debatable, given variability among and within species and the ethical issues involved (Aubin et al., 2011; Winder, R. et al., 2011).

4.4.2.5. *Ex Situ* Conservation

Conservation of plant and animal genetic resources outside of their natural environment—in gardens, zoos, breeding programs, seed banks, or gene banks—has been widely advocated as an "insurance" against both climate change and other sources of biodiversity loss and impoverishment (Khoury et al., 2010). There are many examples of existing efforts of this type, some with global scope (e.g., Millennium Seed Bank, Svalbard Vault, Frozen Ark, Global Genome Initiative, and others; Lermen et al., 2009; Rawson et al., 2011). Knowledge of which genetic variants within a species have more potential for adaptation to climate change could help prioritize the material stored (Michalski et al., 2010).

Several issues remain largely unresolved (Li and Pritchard, 2009). The physiological, institutional, and economic sustainability of such efforts into the indefinite future is unclear. The fraction of the intraspecific variation that needs to be preserved for future viability and how much genetic bias is introduced by collecting relatively small samples from restricted locations, and then later by the selection pressures inadvertently applied during *ex situ* maintenance are unknown. Despite some documented successes, it remains uncertain whether it is always possible to reintroduce species successfully into the wild after generations of *ex situ* conservation.

4.4.3. Consequences and Costs of Inaction and Benefits of Action

Failure to reduce the magnitude or rate of climate change will plausibly lead to changes (often decreases) in the value of ecosystem services provided, or incur costs in order to maintain or restore the services or adapt to their decline. There are several sources of such costs: administration and assessment, implementation, and opportunity costs, including financial cost. Owing to the number of assumptions made, knowledge gaps, and recognized uncertainties, such result should be employed with caution. A systematic review of costs related to ecosystems and climate change by Rodriguez-Labajos (2013) shows that the monetary and non-monetary costs are distributed across all ecosystem service categories. It also discusses the potential and limits of monetary cost calculations, and issues of timing, trade-offs, and the unequal distribution of costs.

A comprehensive monetary estimate of the effects of climate change on ecosystem service provision is not available. The Millennium Ecosystem Assessment (2005c,d,e) included climate change among the direct drivers of ecosystems change and devoted a chapter to the necessary responses. Building on results of the IPCC, the Millennium Ecosystem Assessment offered some estimated costs of action: complying with the Kyoto protocol for industrial countries would range between 0.2 and 2% of GDP; a modest stabilization target of 450 ppm CO_2 in the atmosphere over the 21st century would range from 0.02 to 0.1% of global-average GDP per year. TEEB (2009) underlined priorities in the ecosystem service-climate change coupling (reduction targets in relation to coral reefs, forest carbon markets and accounting, and ecosystem investment for mitigation), without going in depth into analysis of the cost types involved. The Cost of Policy Inaction (COPI) Project (ten Brink et al., 2008) estimated the monetary costs of not meeting the 2010 biodiversity goals. Their model incorporates climate change, among other pressures, through an impaired quality of land, in terms of species abundance in diverse land use categories. They conclude that the cumulative losses

Frequently Asked Questions

FAQ 4.7 | What are the economic costs of changes in ecosystems due to climate change?

Climate change will certainly alter the services provided by most ecosystems, and for high degrees of change, the overall impacts are most likely to be negative. In standard economics, the value of services provided by ecosystems are known as externalities, which are usually outside the market price system, difficult to evaluate, and often ignored.

A good example is the pollination of plants by bees and birds and other species, a service that may be negatively affected by climate change. Pollination is critical for the food supply as well as for overall environmental health. Its value has been estimated globally at US$350 billion for the year 2010 (range of estimates of US$200 to 500 billion).

of welfare due to land use changes, in terms of loss of ecosystem services, could reach an annual amount of EUR 14 trillion (based on 2007 values) in 2050, which may be equivalent to 7% of projected global GDP for that year. Eliasch (2008) estimates the damage costs to forests as reaching US$1 trillion a year by 2100. The study used the probabilistic model employed by Stern (2006), which did not value effects on biodiversity or water-related ecosystem services.

The studies to date agree on the following points. First, climate change has already caused a reduction in ecosystem services that will become more severe as climate change continues. Second, ecosystem-based strategies to mitigate climate change are cost effective, although more difficult to implement (i.e., more costly) in intensively managed ecosystems such as farming lands. Third, accurately estimating the monetary costs of reduction in ecosystem services that are not marketed is difficult. The provision of monetized costs tends to sideline the non-monetized political, social, and environmental costs relevant for decision making. Finally, there is a large funding gap between the cost of actions necessary to protect ecosystem services against climate change and the actual resources available.

In addition to direct costs, further costs may result from trade-offs between services: for example, afforestation for climate mitigation and urban greening for climate adaptation may be costly in terms of water provision (Chisholm, 2010; Jenerette et al., 2011; Pataki et al., 2011). Traditional agriculture preserves soil carbon sinks, supports on-site biodiversity, and uses less fossil fuel than high-input agriculture (Martinez-Alier, 2011) but, due to the typically lower per hectare yields, may require a larger area to be dedicated to cropland. Leaving aside the contested (Searchinger et al., 2008; Plevin et al., 2010) effectiveness of biofuels as a mitigation strategy, there is evidence of their disruptive effect on food security, land tenure, labor rights, and biodiversity in several parts of the world (Obersteiner et al., 2010; Tirado et al., 2010).

4.4.4. Unintended Consequences of Adaptation and Mitigation

Actions taken within the terrestrial and freshwater system domain or in other sectors to mitigate or adapt to climate change can have unintended consequences. Some issues relevant to this section are also found in Section 14.7 and the Working Group III contribution to the AR5.

Several of the alternatives to fossil fuel require extensive use of the land surface and thus have a direct impact on terrestrial ecosystems and an indirect impact on inland water systems (Paterson et al., 2008; Turner et al., 2010). As an illustration, the RPC2.6 scenario involves both bioenergy and renewables as major components of the energy mix (Box 4-1; van Vuuren et al., 2011).

Policy shifts in developed countries favor the expansion of large-scale bioenergy production, which places new pressures on terrestrial and freshwater ecosystems (Searchinger et al., 2008; Lapola et al., 2010), either through direct use of land or water or indirectly by displacing food crops, which must then be grown elsewhere. Over the past decade there has been a global trend to reduced rates of forest loss; it is unclear if this will continue in the face of simultaneously rising food and biofuel demand (Wise et al., 2009; Meyfroidt and Lambin, 2011). The EU Renewable Energy Sources Directive is estimated to have only a moderate influence on European forests provided that the price paid by the bioenergy producers remained below US$50 to 60 per cubic meter of wood (Moiseyev et al., 2011). However, a doubled growth rate for bioenergy until 2030 would have major consequences for the global forest sector, including a reduction of forest stocks in Asia of 2 to 4% (Buongiorno et al. 2011). By 2100 in RCP2.6, bioenergy crops are projected to occupy approximately 4 million km^2, about 7% of global cultivated land projected at the time. Modification of the landscape and the fragmentation of habitats are major influences on extinction risks (Fischer and Lindenmayer, 2007), especially if native vegetation cover is reduced or degraded, human land use is intensive, and "natural" areas become disconnected. Hence, additional extensification of cultivated areas for energy crops may contribute to extinction risks. Some bioenergy crops may be invasive species (Raghu et al., 2006).

Abandoned former agricultural land could be used for biomass production (McAlpine et al., 2009). However, such habitats may be core elements in cultural landscapes of high conservation value, with European species-rich grasslands often developed from abandoned croplands (Hejcman et al., 2013).

Damming of river systems for hydropower can cause fragmentation of the inland water habitat with implications for fish species, and monitoring studies indicate that flooding of ecosystems behind the dams can lead to declining populations, for example, of amphibians (Brandão and Araújo, 2007). Reservoirs can be a sink of CO_2 but also a source of biogenic CO_2 and CH_4; this issue is discussed in WG III AR5 Section 7.8.1.

Wind turbines can kill birds and bats (e.g., Barclay et al., 2007), and inappropriately sited wind farms can negatively impact on bird populations (Drewitt and Langston, 2006). Effects can be reduced by careful siting of turbines, for example by avoiding migration routes (Drewitt and Langston, 2006). Estimating mortality rates is complex and difficult (Smallwood, 2007) but techniques are being developed to inform siting decisions and impact assessments (Péron et al., 2013). Wind farms in Europe and the USA are estimated to cause between 0.3 and 0.4 wildlife fatalities per gigawatt-hour of electricity, compared to approximately 5.2 wildlife fatalities per gigawatt-hour for nuclear and fossil-fuel power stations (Sovacool, 2009; but see Willis, C.K.R. et al., 2010). One study found on-site bird populations to be generally affected more by windfarm construction than subsequent operation, with some populations recovering after construction (Pearce-Higgins et al., 2012).

Large-scale solar farms could impact local biodiversity if poorly sited, but the impact can be reduced with appropriate planning (Tsoutsos et al., 2005). Solar photovoltaic installations can decrease local surface albedo, giving a small positive radiative forcing. There are some plausible local circumstances in which this may be a consideration, but in general the climate effect is estimated to be 30 times smaller than the avoided radiative forcing arising from substituting fossil fuels with PV (Nemet, 2009).

Relocation or expansion of agricultural areas and settlements as climate change adaptation measures could pose risks of habitat fragmentation and loss similar to those discussed above in the context of mitigation through bio-energy. Assisted migration (see Section 4.4.2.4) may directly conflict with other conservation priorities, for example by facilitating the introduction of invasive species (Maclachlan et al., 2007).

4.5. Emerging Issues and Key Uncertainties

Detecting the presence and location of thresholds in ecosystem response to climate change, specifically the type of thresholds characterized as tipping points, remains a major source of uncertainty with high potential consequences. In general (Field et al., 2007), negative feedbacks currently dominate the climate-ecosystem interaction. For most ecological processes, increasing magnitude of warming shifts the balance toward positive rather than negative feedbacks (Field et al., 2007). In several regions, such as the boreal ecosystems, positive feedbacks may become dominant, under moderate warming. For positive feedbacks to propagate into "runaway" processes leading to a new ecosystem state, the strength of the feedback has to exceed that of the initial perturbation. This has not as yet been demonstrated for any large-scale, plausible, and immanent ecological process, but the risk is non-negligible and the consequences if it did occur would be severe; thus further research is needed.

The issue of biophysical interactions between ecosystem state and the climate, over and above the effects mediated through GHGs, is emerging as significant in many areas. Such effects include those caused by changes in surface reflectivity (albedo) or the partitioning of energy between latent energy and sensible heat.

Uncertainty in predicting the response of terrestrial and freshwater ecosystems to climate and other perturbations, particularly at the local scale, remains a major impediment to determining prudent levels of permissible change. A significant source of this uncertainty stems from the inherent complexity of ecosystems, especially where they are coupled to equally complex social systems. The high number of interactions can lead to cascading effects (Biggs et al., 2011). Some of this uncertainty can be reduced by better systems understanding, but some will remain irreducible because of the failure of predictive models when faced with certain types of complexity (such as those which lead to mathematical bifurcations, a problem that is well known in climate science). Probabilistic statements about the range of outcomes are possible in this context, but ecosystem science is as yet mostly unable to conduct such analyses routinely and rigorously. One consequence is the ongoing difficulty in attributing observed changes unequivocally to climate change. More comprehensive monitoring is a key element of the solution.

The consequences for species interactions of differing phenological or movement-based responses to climate change are insufficiently known and may make projections based on individual species models unreliable.

Studies of the combined effects of multiple simultaneous elements of global change, such as the effects of elevated CO_2 and rising tropospheric ozone on plant productivity—which have critical consequences for the future sink strength of the biosphere, as they are of similar magnitude but opposite sign—are needed as a supplement to the single-factor experiments. For example, uncertainty on the magnitude of CO_2 fertilization is key for forest responses to climate change, particularly in tropical forests, woodlands, and savannas (Cox et al., 2013; Huntingford et al., 2013).

The effects of changes in the frequency or intensity of climate-related extreme events, such as floods, cyclones, heat waves, and exceptionally large fires on ecosystem change are probably equal to or greater than shifts in the mean values of climate variables. These effects are insufficiently studied and, in particular, are seldom adequately represented in ESMs.

Understanding of the rate of climate change that can be tracked or adapted to by organisms is as important as understanding the magnitude of change they can tolerate. Despite being explicitly required under Article 2 of the UNFCCC, rate studies are currently less developed and more uncertain than magnitude (equilibrium) studies. This includes evidence for the achievable migration rates of a range of species as well as the rate of micro-evolutionary change.

The capacity for, and limits to, ecological and evolutionary adaptive processes are known only in a few cases. The development and testing of human-assisted adaptation strategies for their cost-effectiveness in reducing risk are prerequisites for their widespread adoption.

The costs of the loss of biodiversity and ecosystem services as a result of climate change are known for only a few cases, or are associated with large uncertainties, as are the costs and benefits of assisting ecosystems and species to adapt to climate change.

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5 Coastal Systems and Low-Lying Areas

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Executive Summary

Coastal systems are particularly sensitive to three key drivers related to climate change: sea level, ocean temperature, and ocean acidity (*very high confidence*). {5.3.2, 5.3.3.4, 5.3.3.5} Despite the lack of attribution of observed coastal changes, there is a long-term commitment to experience the impacts of sea level rise because of a delay in its response to temperature (*high confidence*). {5.5.8} In contrast, coral bleaching and species ranges can be attributed to ocean temperature change and ocean acidity. {5.4.2.2, 5.4.2.4} For many other coastal changes, the impacts of climate change are difficult to tease apart from human-related drivers (e.g., land use change, coastal development, pollution) (*robust evidence*, *high agreement*).

Coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion due to relative sea level rise (RSLR; *very high confidence*). In the absence of adaptation, beaches, sand dunes, and cliffs currently eroding will continue to do so under increasing sea level (*high confidence*). {5.4.2.1, 5.4.2.2} Large spatial variations in the projected sea level rise together with local factors means RSLR at the local scale can vary considerably from projected global mean sea level rise (GMSLR) (*very high confidence*). {5.3.2} Changes in storms and associated storm surges may further contribute to changes in sea level extremes but the small number of regional storm surge studies, and uncertainty in changes in tropical and mid-latitude cyclones at the regional scale, means that there is *low confidence* in projections of storm surge change {5.3.3.2} Both RSLR and impacts are also influenced by a variety of local processes unrelated to climate (e.g., subsidence, glacial isostatic adjustment, sediment transport, coastal development) (*very high confidence*).

Acidification and warming of coastal waters will continue with significant negative consequences for coastal ecosystems (*high confidence*). The increase in acidity will be higher in areas where eutrophication or coastal upwellings are an issue. It will have negative impacts for many calcifying organisms (*high confidence*). {5.4.2.2} Warming and acidification will lead to coral bleaching, mortality, and decreased constructional ability (*high confidence*), making coral reefs the most vulnerable marine ecosystem with little scope for adaptation. {5.4.2.4, Box CC-OA} Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and sea temperature extremes as well as through the impact of invasive subtropical species (*high confidence*). {5.4.2.3}

The population and assets exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, and urbanization (*high confidence*). The exposure of people and assets to coastal risks has been rapidly growing and this trend is expected to continue. {5.3.4.1, 5.4.3.1} Humans have been the primary drivers of changes in coastal aquifers, lagoons, estuaries, deltas, and wetlands (*very high confidence*) and are expected to further exacerbate human pressures on coastal ecosystems resulting from excess nutrient input, changes in runoff, and reduced sediment delivery (*high confidence*). {5.3.4.2, 5.3.4.3, 5.3.4.4}

For the 21st century, the benefits of protecting against increased coastal flooding and land loss due to submergence and erosion at the global scale are larger than the social and economic costs of inaction (*limited evidence*, *high agreement*). Without adaptation, hundreds of millions of people will be affected by coastal flooding and will be displaced due to land loss by year 2100; the majority of those affected are from East, Southeast, and South Asia (*high confidence*). {5.3.4.1, 5.4.3.1} At the same time, protecting against flooding and erosion is considered economically rational for most developed coastlines in many countries under all socioeconomic and sea level rise scenarios analyzed, including for the 21st century GMSLR of above 1 m (*limited evidence*, *high agreement*). {5.5.5}

The relative costs of adaptation vary strongly between and within regions and countries for the 21st century (*high confidence*). Some low-lying developing countries (e.g., Bangladesh, Vietnam) and small islands are expected to face very high impacts and associated annual damage and adaptation costs of several percentage points of gross domestic product (GDP). {5.5.5} Developing countries and small islands within the tropics dependent on coastal tourism will be impacted directly not only by future sea level rise and associated extremes but also by coral bleaching and ocean acidification and associated reductions in tourist arrivals (*high confidence*). {5.4.3.4}

The analysis and implementation of coastal adaptation toward climate-resilient and sustainable coasts has progressed more significantly in developed countries than in developing countries (*high confidence*). Given ample adaptation options, more proactive responses can be made and based on technological, policy related, financial, and institutional support. Observed successful adaptation includes major projects (e.g., Thames Estuary, Venice Lagoon, Delta Works) and specific practices in both developed countries (e.g., Netherlands, Australia) and developing countries (e.g., Bangladesh). {5.5.4.2} More countries and communities carry out coastal adaptation measures including those based on integrated coastal zone management, local communities, ecosystems, and disaster reduction, and these measures are mainstreamed into relevant strategies and management plans (*high confidence*). {5.5.4, 5.5.5}

5.1. Introduction

This chapter presents an updated picture of the impacts, vulnerability, and adaptation of coastal systems and low-lying areas to climate change, with sea level rise perceived as the most important risk for human systems. Unlike the coastal chapter in the previous assessment (Fourth Assessment Report, AR4), materials pertinent to the oceans are not covered here but in two new ocean chapters (Chapters 6 and 30). As in AR4, polar coasts are in another chapter (Chapter 28); small islands are also considered separately (Chapter 29) so an in-depth discussion is not provided herein.

The topics covered in this chapter follow the outline for sectoral chapters approved by the IPCC. An Executive Summary summarizes the key messages with a line of sight to the supporting sections in the chapter.

This chapter consists of six sections, with this first section dealing with progress in knowledge from AR4 to AR5 (Fifth Assessment Report), scope of chapter, and new developments. Section 5.2 defines the coastal systems and climate and non-climate drivers. The coastal systems include both natural systems and human systems, and this division is generally followed throughout the chapter. The climate and non-climate drivers are assessed in Section 5.3, followed by the impacts, vulnerabilities, and risks in Section 5.4. Section 5.5 deals with adaptation and managing risks. Information gaps, data gaps, and research needs are assessed in Section 5.6. There is one box on a specific example and reference to three cross-chapter boxes.

In AR4, the coastal chapter assessed the impact of climate change and a global sea level rise up to 0.59 m in the 2090s. The coastal systems were considered to be affected mainly by higher sea levels, increasing temperatures, changes in precipitation, larger storm surges, and increased ocean acidity. Human activities had continued to increase their pressure on the coasts with rapid urbanization in coastal areas and growth of megacities with consequences on coastal resources. Regionally, South, Southeast, and East Asia; Africa; and small islands were identified as most vulnerable. The AR4 chapter offered a range of adaptation measures, many under the Integrated Coastal Zone Management (ICZM) framework that could be carried out in both developed and developing countries, but recognized that the latter would face more challenges. Various issues on increasing the adaptive capacity or increasing the resilience of coastal communities were discussed. The unavoidability of sea level rise in the long term, even with stringent mitigation, was noted, with adaptation becoming an urgent issue.

A number of key issues related to the coasts have arisen since AR4. There is now better understanding of the natural systems, their ecosystem functions, their services and benefits to humanity, and how they can be affected by climate change. Their linkages landward to the watersheds and seaward to the seas and oceans need to be considered for a more integrated assessment of climate change impacts. The global mean sea level rise (GMSLR) is projected to be 0.28 to 0.98 m by 2100 (Table 5-2), although with regional variations and local factors the local sea level rise can be higher than that projected for the GMSLR. This has serious implications for coastal cities, deltas, and low-lying states. While higher rates of coastal erosion are generally expected under rising sea levels, the complex inter-relationships between the geomorphological and ecological attributes of the coastal system (Gilman et al., 2006; Haslett, 2009) and the relevant climate and oceanic processes need to be better established at regional and local scales. Such complex inter-relationships can be influenced by different methods and responses of coastal management.

Also of concern is ocean acidification. Together with warming, it causes coral reefs to lose their structural integrity, negatively implicating reef communities and shore protection (Sheppard et al., 2005; Manzello et al., 2008; see Boxes CC-OA, CC-CR). Acidification has potential impacts of reduced calcification in shellfish and impacts on commercial aquaculture (Barton et al., 2012). Since AR4, a significant number of new findings regarding the impacts of climate change on human settlements and key coastal systems such as rocky coasts, beaches, estuaries, deltas, salt marshes, mangroves, coral reefs, and submerged vegetation have become available and are reviewed in this chapter. However, uncertainties regarding projections of potential impacts on coastal systems remain generally high.

This chapter also provides advances in both vulnerability assessments and the identification of potential adaptation actions, costs, benefits, and trade-offs. A large number of new studies estimate the costs of inaction versus potential adaptation. Coastal adaptation has become more widely used, with a wider range of approaches and frameworks such as integrated coastal management, ecosystem-based adaptation, community-based adaptation, and disaster risk reduction and management.

Climate change will interact differently with the variety of human activities and other drivers of change along coastlines of developed and developing countries. For example, on the coastlines of developed countries, changes in weather and climate extremes and sea level rise may impact the demand for housing, recreational facilities, and construction of renewable energy infrastructure on the coast (Hadley, 2009), including critical infrastructures such as transportation, ports, and naval bases. Along the coasts of developing countries, weather and climate extremes affect a wide range of economic activities supporting coastal communities and pose an additional risk to many of the fastest growing low-lying urban areas, such as in Bangladesh and China (McGranahan et al., 2007; Smith, 2011).

5.2. Coastal Systems

Coastal systems and low-lying areas, also referred to as coasts in this assessment, include all areas near mean sea level. Generally, there is no single definition for the coast and the coastal zone/area, where the latter emphasizes the area or extent of the coastal ecosystems. In relation to exposure to potential sea level rise, the low-elevation coastal zone (LECZ) has been used in recent years with reference to specific area and population up to 10 m elevation (Vafeidis et al., 2011).

Coastal systems are conceptualized to consist of both natural and human systems (Figure 5-1). The natural systems include distinct coastal features and ecosystems such as rocky coasts, beaches, barriers and sand dunes, estuaries and lagoons, deltas, river mouths, wetlands, and coral reefs. These elements help define the seaward and landward boundaries of the coast. In spite of providing a wide variety of regulating, provisioning, supporting, and cultural services (MEA, 2005), they have

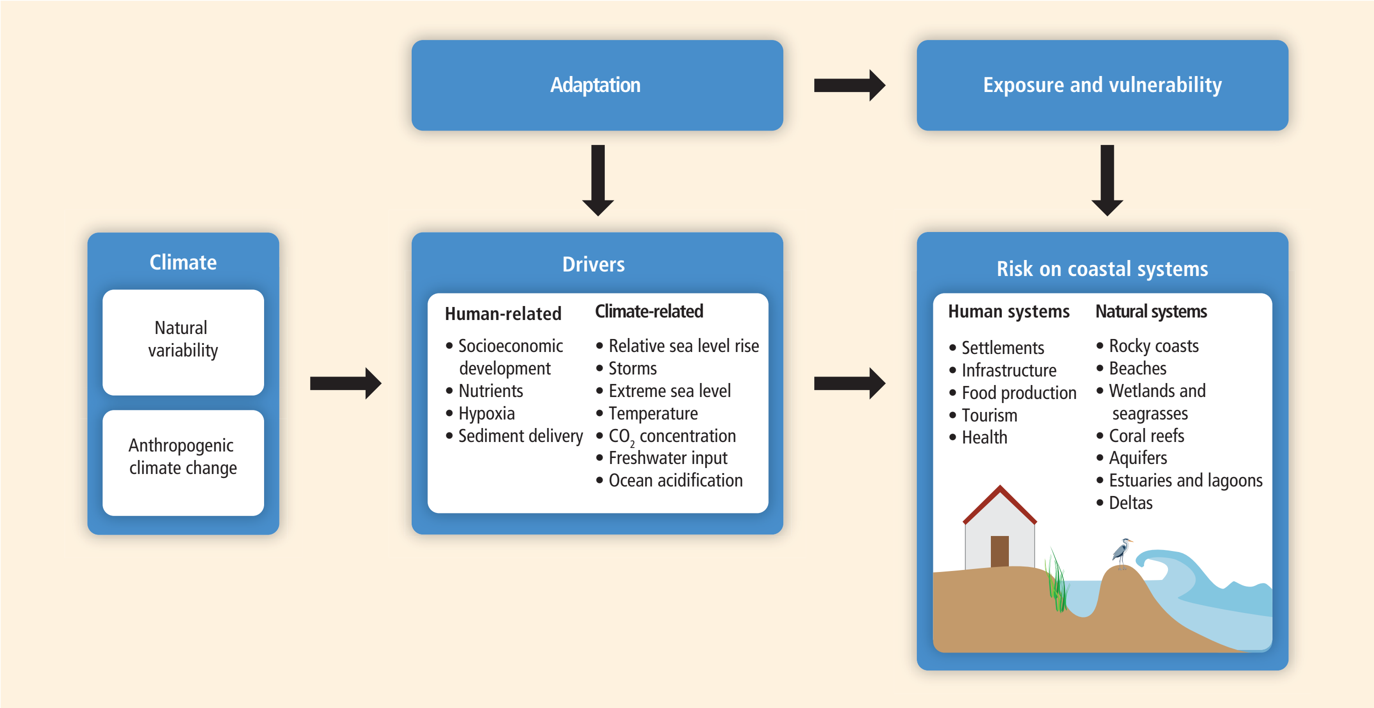

Figure 5-1 | Climate, just as anthropogenic or natural variability, affects both climate and human related drivers. Risk on coastal systems is the outcome of integrating drivers' associated hazards, exposure, and vulnerability. Adaptation options can be implemented either to modify the hazards or exposure and vulnerability, or both.

been altered and heavily influenced by human activities, with climate change constituting only one among many pressures these systems are facing. The human systems include the built environment (e.g., settlements, water, drainage, as well as transportation infrastructure and networks), human activities (e.g., tourism, aquaculture, fisheries), as well as formal and informal institutions that organize human activities (e.g., policies, laws, customs, norms, and culture). The human and natural systems form a tightly coupled socio-ecological system (Berkes and Folke, 1998; Hopkins et al., 2012).

5.3. Drivers

5.3.1. Introduction

In AR4, changes in climate drivers (i.e., any climate-induced factor that directly or indirectly causes a change), including sea level rise, were projected for different Special Report on Emissions Scenarios (SRES) emissions scenarios (IPCC, 2000). Consequently, to date, most of the impacts and vulnerability assessments of climate change in coastal areas are based on SRES A2, A1B, B2, and A1F1 scenarios. Since AR4 a new scenario process has been initiated to replace the SRES scenarios with Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) (Moss et al., 2010). The RCPs are scenarios specifying concentrations, rather than emissions, thereby avoiding differences in concentrations of long-lived greenhouse gas (GHG) and aerosol concentrations for the same emissions scenarios that can arise from the use of different models (van Vuuren et al., 2011). For a comparison between RCP and SRES scenarios, see WGI AR5 Box 1.2. In addition, Extended Concentration Pathways (ECPs) have been introduced for the 2100–2300 period (Meinhausen et al., 2011), providing the opportunity to assess the long-term commitment to sea level rise, which is *virtually certain* to continue beyond 2500 unless global temperature declines (WGI AR5 Chapter 1; Section 13.5.2).

The SSPs provide representative qualitative story lines (narratives) of world development together with quantitative pathways of key socioeconomic variables such as gross domestic product (GDP) and population. A preliminary list of five SSPs has been proposed (Arnell et al., 2011; O'Neill et al., 2012), and work to further refine them is ongoing (Kriegler et al. 2012; Van Vuuren et al., 2012). SSPs do not include assumptions on mitigation policy and are thus independent from RCPs in the sense that the same SSP may lead to different concentration levels and consequently rises in sea level depending on the level of mitigation reached (Arnell et al., 2011; O'Neill et al., 2012). Table 5-1 summarizes the main climate-related drivers for the coastal systems.

5.3.2. Relative Sea Level Rise

Assessments of coastal impacts, vulnerability, and adaptation need to consider relative sea level rise (RSLR), which includes climate-induced GMSLR (Section 5.3.2.1) and regional variations (Section 5.3.2.2) as well as local non-climate-related sea level changes (Section 5.3.2.3). RSLR poses a significant threat to coastal systems and low-lying areas around the globe, leading to inundation and erosion of coastlines and contamination of freshwater reserves and food crops (Nicholls, 2010). Sea level rise due to thermal expansion as the oceans warm, together with meltwater from glaciers, icecaps, and ice sheets of Greenland and Antarctica, are the major factors that contribute to RSLR globally. However, regional variations in the rate of rise occur because of ocean circulation patterns and interannual and decadal variability (e.g., Zhang

5

Table 5-1 | Main climate-related drivers for coastal systems, their trends due to climate change, and their main physical and ecosystem effects.

Climate-related driver	Physical/chemical effects	Trends	Projections	Progress since AR4
Sea level	Submergence, flood damage, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change).	Global mean sea level *very likely* increase (Section 5.3.2.2; WGI AR5 Sections 3.7.2, 3.7.3).	Global mean sea level *very likely* increase (see Table 5.1; WGI AR5 Section 13.5.1). Regional variability (Section 5.3.2.2; WGI AR5 Chapter 13).	Improved confidence in contributions to observed sea level. More information on regional and local sea level rise.
Storms: tropical cyclones (TCs), extratropical cyclones (ETCs)	Storm surges and storm waves, coastal flooding, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change). Coastal infrastructure damage and flood defense failure.	TCs (Box 5-1, WGI AR5 Section 2.6.3): *low confidence* in trends in frequency and intensity due to limitations in observations and regional variability. ETCs (Section 5.3.3.1; WGI AR5 Section 2.6.4): *likely* poleward movement of circulation features but *low confidence* in intensity changes.	TCs (Box 5-1): *likely* decrease to no change in frequency; *likely* increase in the most intense TCs. ETCs (Section 5.3.3.1): *high confidence* that reduction of ETCs will be small globally. *Low confidence* in changes in intensity.	Lowering of confidence of observed trends in TCs and ETCs since AR4. More basin-specific information on storm track changes.
Winds	Wind waves, storm surges, coastal currents, land coastal infrastructure damage.	*Low confidence* in trends in mean and extreme wind speeds (Section 5.3.3.2, SREX, WGI AR5 Section 3.4.5).	*Low confidence* in projected mean wind speeds. *Likely* increase in TC extreme wind speeds (Section 5.3.3.2, SREX).	Winds not specifically addressed in AR4.
Waves	Coastal erosion, overtopping and coastal flooding.	*Likely* positive trends in Hs in high latitudes (Section 5.3.3.2; WGI AR5 Section 3.4.5).	*Low confidence* for projections overall but *medium confidence* for Southern Ocean increases in Hs (Section 5.3.3.2).	Large increase in number of wave projection studies since AR4.
Extreme sea levels	Coastal flooding erosion, saltwater intrusion.	*High confidence* of increase due to global mean sea level rise (Section 5.3.3.3; WGI AR5 Chapter 13).	*High confidence* of increase due to global mean sea level rise, *low confidence* of changes due to storm changes (Section 5.3.3.3; WGI AR5 Section 13.5).	Local subsidence is an important contribution to regional sea level rise in many locations.
Sea surface temperature (SST)	Changes to stratification and circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality, poleward species migration; increased algal blooms.	*High confidence* that coastal SST increase is higher than global SST increase (Section 5.3.3.4).	*High confidence* that coastal SSTs will increase with projected temperature increase (Section 5.3.3.4).	Emerging information on coastal changes in SSTs.
Freshwater input	Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply.	*Medium confidence* (*limited evidence*) in a net declining trend in annual volume of freshwater input (Section 5.3.3.6).	*Medium confidence* for general increase in high latitudes and wet tropics and decrease in other tropical regions (Section 5.3.3.6).	Emerging information on freshwater input.
Ocean acidity	Increased CO_2 fertilization; decreased seawater pH and carbonate ion concentration (or "ocean acidification").	*High confidence* of overall increase, with high local and regional variability (Section 5.3.3.5).	*High confidence* of increase at unprecedented rates but with local and regional variability (Box CC-OA).	Coastal ocean acidification not specifically addressed in AR4. Considerable progress made in chemical projections and biological impacts.

SREX = IPCC 2012 Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.

and Church, 2012; Ganachaud et al., 2013) and glacial isostatic rebound and tectonic movement. Subsidence of coastal land from sediment compaction due to building loads, harbor dredging, changes in sediment supply that cause erosion/accretion, and subsurface resource extraction (e.g., groundwater, gas and petroleum; Syvitski et al., 2009) may also contribute to RSLR locally and therefore requires consideration in coastal impact studies. Sea level impacts are most pronounced during episodes of extreme sea levels and these are discussed in Section 5.3.3.

5.3.2.1. Global Mean Sea Level

It is *very likely* that global mean sea level rose at a mean rate of 1.7 [1.5 to 1.9] mm yr^{-1} between 1900 and 2010 and at a rate 3.2 [2.8 to 3.6] mm yr^{-1} from 1993 to 2010 (WGI AR5 Section 13.2.2). Ocean thermal expansion and melting of glaciers have been the largest contributors, accounting for more than 80% of the GMSLR over the latter period (WGI AR5 Section 13.3.1). Future rates of GMSLR during the 21st century are projected to exceed the observed rate for the period 1971–2010 of 2.0 [1.7 to 2.3] mm yr^{-1} for all RCP scenarios (WGI AR5 Table 13.1). Table 5-2 summarizes the *likely* ranges of 21st century GMSLR as established by the Working Group I contribution to this Assessment Report.

From a coastal risk management perspective (Nicholls et al., 2013) assessments of impacts, vulnerabilities, and adaptation have been using GMSLR scenarios above the ranges put forward by WGI reports of AR4 (Meehl et al., 2007; Table 10.7) and AR5 (WGI AR5 Table 13.5). The ranges estimated by WGI of AR4 and AR5 include only those components of GMSLR that can be quantified using process-based models (i.e., models derived from the laws of physics; WGI AR5 Glossary). The ranges given in AR4 thus explicitly excluded contributions to GMSLR resulting from changes in ice flows from the ice sheets of Greenland and Antarctica because at that time process-based models were not able to assess this with sufficient confidence (Meehl et al., 2007; WGI AR5 Section 4.4.5). Since then, understanding has increased and the *likely* range of GMSLR given in AR5 now includes ice sheet flow contributions. *Likely*, however, means that there is still a 0 to 33% probability of GMSLR beyond this range, and coastal risk management needs to consider this. WGI does not assign probabilities to GMSLR beyond the *likely* range, because this cannot be done with the available process-based models. WGI, however, assigns *medium confidence* that 21st century GMSLR does not exceed the likely range by several tenths of a meter (WGI AR5 Section 13.5.1). When using other approaches such as semi-empirical models, evidence from past climates and physical constraints on ice-sheet dynamics GMSLR upper bounds of up to 2.4 m by 2100 have been estimated, but there is *low agreement* on these higher estimates and no consensus on a 21st century upper bound (WGI AR5 Section 13.5.3). Coastal risk management is thus left to choose an upper bound of GMSLR to consider based on which level of risk is judged to be acceptable in the specific case. The Dutch Delta Programme, for example, considered a 21st century GMSLR of 1.3 m as the upper bound.

It is *virtually certain* that sea level rise will continue beyond the 21st century, although projections beyond 2100 are based on fewer and simpler models that include lower resolution coupled climate models for thermal expansion and ice sheet models coupled to climate models to project ice sheet contributions. The basis for the projections are the Extended Concentration Pathways (ECPs), and projections are provided for low, medium, and high scenarios that relate to atmospheric GHG concentrations <500, 500 to 700, and >700 ppm respectively (WGI AR5 Section 13.5.2). Projections of GMSLR up to 2500 are also summarized in Table 5-2.

5.3.2.2. Regional Sea Level

Sea level rise will not be uniform in space and time. Natural modes of climate variability influence sea levels in different regions of the globe and this will affect the rate of rise on interannual and interdecadal time periods. For example, in the equatorial Pacific, sea levels can vary from the global mean by up to 40 cm due to El Niño-Southern Oscillation (ENSO; e.g., Walsh et al., 2012) and this can strongly influence trends on decadal scales. Regional variations in the rate of sea level rise on the coast can arise from climate and ocean dynamic processes such as changes in winds and air pressure, air-sea heat and freshwater fluxes, and ocean currents and their steric properties (Timmermann et al., 2010; WGI AR5 FAQ 13.1). Although the vast majority of coastlines are experiencing sea level rise, coastlines near current and former glaciers and ice sheets are experiencing relative sea level fall (Milne et al., 2009; WGI AR5 FAQ 13.1). This is because the gravitational attraction of the ice sheet decreases as it melts and exerts less pull on the oceans and also because the land tends to rise as the ice melts, the shape of the sea floor changes under the reduced load of the ice sheets, and the change in mass distribution alters the Earth's rotation (WGI AR5 FAQ 13.1; Gomez et al., 2010). In terms of absolute sea level change, approximately 70% of the global coastlines are projected to experience sea level change that is within 20% of the global mean sea level change (WGI AR5 Section 13.6.5).

5.3.2.3. Local Sea Level

Besides the effect of long-term vertical land movement on regional sea level, RSLR can occur locally due to subsidence or uplifts of coastal plains as well as due to other natural causes. Natural subsidence can occur because of sediment compaction and loading, as in the Mississippi River, and other deltas (Törnqvist et al., 2008; Dokka, 2011; Marriner et al., 2012). Tectonic movements, both sustained and abrupt, have brought about relative sea level changes. The Great East Japan Earthquake in 2011 caused subsidence of up to 1.2 m of the Pacific coast of northeast Japan (Geospatial Information Authority of Japan, 2011). The Sumatra-Andaman earthquake in 2004 and subsequent earthquakes in 2005 produced vertical deformation ranging from uplift of 3 m to subsidence of 1 m (Briggs et al., 2006). These movements are especially important in coastal zones located near active plate margins.

Anthropogenic causes of RSLR include sediment consolidation from building loads, reduced sediment delivery to the coast, and extraction of subsurface resources such as gas, petroleum, and groundwater. Subsidence rates may also be sensitive to the rates of oil and gas removal (e.g., Kolker et al., 2011). Syvitski et al. (2009) estimate that the majority of the world's largest deltas are currently subsiding at rates that are considerably larger than the current rates of sea level rise because of coastal sediment starvation due to substantial dam building over the 20th century or sediment compaction through natural or anthropogenic activities. Many large cities on deltas and coastal plains have subsided during the last 100 years: ~4.4 m in eastern Tokyo, ~3 m in the Po delta, ~2.6 m in Shanghai, and ~1.6 m in Bangkok (Syvitski et al., 2009; Teatini et al., 2011). Loads from massive buildings and other large structures can also increase sediment compaction and subsidence (Mazzotti et al., 2009). RSLR can exceed GMSLR by an order of magnitude, reaching more than 10 cm yr^{-1}, and it is estimated that the delta surface

Table 5-2 | Projections of global mean sea level rise in meters relative to 1986–2005 are based on ocean thermal expansion calculated from climate models, the contributions from glaciers, Greenland and Antarctica from surface mass balance calculations using climate model temperature projections, the range of the contribution from Greenland and Antarctica due to dynamical processes, and the terrestrial contribution to sea levels, estimated from available studies. For sea levels up to and including 2100, the central values and the 5–95% range are given whereas for projections from 2200 onwards, the range represents the model spread due to the small number of model projections available and the high scenario includes projections based on RCP6.0 and RCP8.5. Source: WGI AR5 Summary for Policymakers and Sections 12.4.1, 13.5.1, and 13.5.4.

Emission scenario	Representative Concentration Pathway (RCP)	2100 CO_2 concentration (ppm)	Mean sea level rise (m)		Emission scenario	Mean sea level rise (m)		
			2046–2065	2100		2200	2300	2500
Low	2.6	421	0.24 [0.17–0.32]	0.44 [0.28–0.61]	Low	0.35–0.72	0.41–0.85	0.50–1.02
Medium low	4.5	538	0.26 [0.19–0.33]	0.53 [0.36–0.71]	Medium	0.26–1.09	0.27–1.51	0.18–2.32
Medium high	6.0	670	0.25 [0.18–0.32]	0.55 [0.38–0.73]	High	0.58–2.03	0.92–3.59	1.51–6.63
High	8.5	936	0.29 [0.22–0.38]	0.74 [0.52–0.98]				

area vulnerable to flooding could increase by 50% for 33 deltas around the world under the sea level rise as projected for 2100 by the IPCC AR4 (Syvitski et al., 2009).

Clearly large regional variations in the projected sea level rise, together with local factors such as subsidence, indicates that RSLR can be much larger than projected GMSLR and therefore is an important consideration in impact assessments (*very high confidence*).

5.3.3. Climate-Related Drivers

Increasing GHGs in the atmosphere produce changes in the climate system on a range of time scales that impact the coastal physical environment. On shorter time scales, physical coastal impacts such as inundation, erosion, and coastal flooding arise from severe storm-induced surges, wave overtopping, and rainfall runoff. On longer time scales, wind and wave climate change can cause changes in sediment transport at the coast and associated changes in erosion or accretion. Natural modes of climate variability, which can affect severe storm behavior and wind and wave climate, may also undergo anthropogenic changes in the future. Ocean and atmospheric temperature change can affect species distribution with impacts on coastal biodiversity. Carbon dioxide (CO_2) uptake in the ocean increases ocean acidity and reduces the saturation state of carbonate minerals, essential for shell and skeletal formation in many coastal species. Changes in freshwater input can alter coastal ocean salinity concentrations. Past and future changes to these physical drivers are discussed in this section (see also Table 5-1).

5.3.3.1. Severe Storms

Severe storms such as tropical and extratropical cyclones (ETCs) can generate storm surges over coastal seas. The severity of these depends on the storm track, regional bathymetry, nearshore hydrodynamics, and the contribution from waves. Globally there is *low confidence* regarding changes in tropical cyclone activity over the 20th century owing to changes in observational capabilities, although it is *virtually certain* that there has been an increase in the frequency and intensity of the strongest tropical cyclones in the North Atlantic since the 1970s (WGI AR5 Section 2.6). In the future, it is *likely* that the frequency of tropical cyclones globally will either decrease or remain unchanged, but there will be a *likely* increase in global mean tropical cyclone precipitation rates and maximum wind speed (WGI AR5 Section 14.6).

ETCs occur throughout the mid-latitudes of both hemispheres, and their development is linked to large-scale circulation patterns. Assessment of changes in these circulation features reveals a widening of the tropical belt, poleward shift of storm tracks and jet streams, and contraction of the polar vortex; this leads to the assessment that it is *likely* that, in a zonal mean sense, circulation features have moved poleward (WGI AR5 Sections 2.7.5 to 2.7.8) but there is *low confidence* regarding regional changes in intensity of ETCs (e.g., Seneviratne et al., 2012). With regard to future changes, a small poleward shift is *likely* in the Southern Hemisphere but changes in the Northern Hemisphere are basin specific and of *lower confidence* (WGI AR5 Section 14.6.3). Globally, it is *unlikely* that the number of ETCs will fall by more than a few percent due to anthropogenic climate change (*high confidence*; WGI AR5 Section 14.6.3).

5.3.3.2. Extreme Sea Levels

Extreme sea levels are those that arise from combinations of factors including astronomical tides, storm surges, wind waves and swell, and interannual variability in sea levels. Storm surges are caused by the falling atmospheric pressures and surface wind stress associated with storms such as tropical and ETCs and therefore may change if storms are affected by climate change. To date, however, observed trends in extreme sea levels are mainly consistent with mean sea level (MSL) trends (e.g., Marcos et al., 2009; Haigh et al., 2010; Menendez and Woodworth, 2010; Losada et al., 2013) indicating that MSL trends rather than changes in weather patterns are responsible.

Assuming that sea level extremes follow a simple extreme value distribution (i.e., a Gumbel distribution), and accounting for the uncertainty in projections of future sea level rise, Hunter (2012) has developed a technique for estimating a sea level allowance, that is, the minimum height that structures would need to be raised in a future period so that the number of exceedances of that height remains the same as under present climate conditions (Figure 5-2). Such an allowance can be factored into adaptive responses to rising sea levels. It should be noted, however, that extreme sea level distributions might not follow a simple Gumbel distribution (e.g., Tebaldi et al., 2012) owing to different factors influencing extreme levels that may not be measured by tide gauges (e.g., Hoeke et al., 2013).

Regarding future changes to storm surges, hydrodynamic models forced by climate models have been used in several extratropical regional studies such as the northeast Atlantic (e.g., Debenard and Roed, 2008; Wang et al., 2008; Sterl et al., 2009) and southern Australia (Colberg and McInnes, 2012). These studies show strong regional variability and sensitivity to the choice of Global Climate Model (GCM) or Regional Climate Model (RCM). The effect of future tropical cyclone changes on storm surges has also been investigated in a number of regions using a range of different methods. These include methods to stochastically generate and/or perturb cyclones within background environmental conditions that represent historical (e.g., Harper et al., 2009) and GCM-represented future conditions (e.g., Mousavi et al., 2011; Lin et al., 2012). Regional studies include Australia's tropical east coast (Harper et al., 2009), Louisiana (Smith et al., 2010), Gulf of Mexico (Mousavi et al., 2011), India (Unnikrishnan et al., 2011), and New York (Lin et al., 2012), and the details of the methods and findings vary considerably between the studies. While some studies indicate for some regions increase to extreme sea levels due to changes in storms, others indicate the opposite. In general, the small number of regional storm surge studies together with the different atmospheric forcing factors and modeling approaches means that there is *low confidence* in projections of storm surges due to changes in storm characteristics. However, observed upward trends in MSL together with projected increases for 2100 and beyond indicate that coastal systems and low-lying areas will increasingly experience extreme sea levels and their adverse impacts (*high confidence*) (see also WGI AR5 Section 13.7).

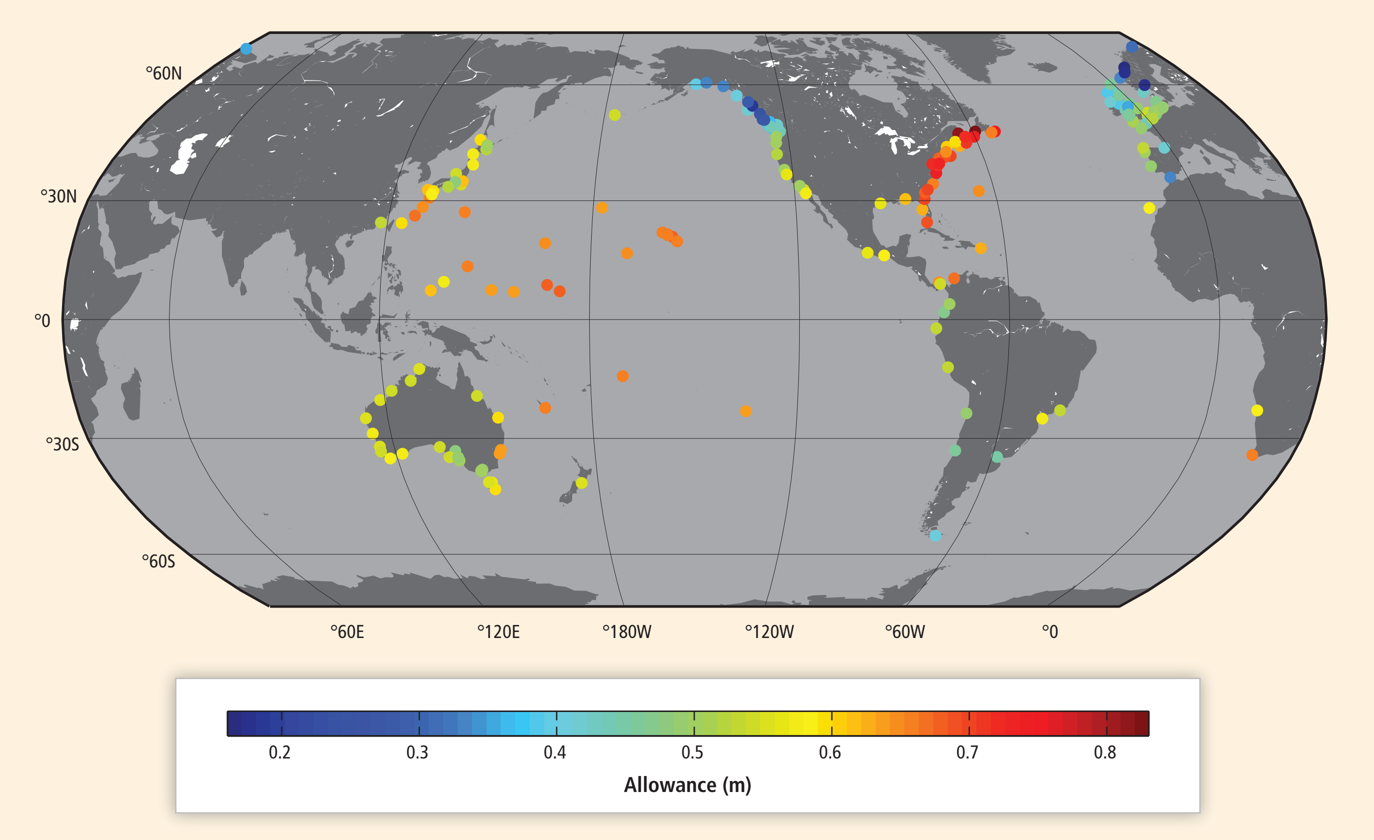

Figure 5-2 | The estimated increase in height (m) that flood protection structures would need to be raised in the 2081–2100 period to preserve the same frequency of exceedances that was experienced for the 1986–2005 period, shown for 182 tide gauge locations and assuming regionally varying relative sea level rise projections under an Representative Concentration Pathway 4.5 (RCP4.5) scenario (adapted from Hunter et al., 2013).

5.3.3.3. Winds and Waves

Changes in wind climate affect large-scale wave climate. Winds also influence longshore current regimes and hence upwelling systems (Narayan et al., 2010; Miranda et al., 2012; see also Sections 6.3.3, 6.3.5). Energy dissipation via wave breaking contributes to longshore and cross-shore currents, elevated coastal sea levels through wave set-up, and run-up and beach erosion. Changes to wind and wave climate therefore can affect sediment dynamics and shoreline processes (e.g., Aargaard et al., 2004; Reguero et al., 2013), and extreme winds and waves are a threat to coastal populations. The coastal impacts of wave climate change are also a function of wave direction and period as well as the coastline itself, which can influence shoaling and refraction. Long period swell, which dominates the wave energy field, poses a significant danger to coastal and offshore structures and shipping (e.g., Semedo et al., 2011) and can causes significant flooding of coastlines with steep shelf margins (Hoeke et al., 2013).

There is *low confidence* in trends calculated from measurements of mean and extreme winds and their causes due to the limited length of records and uncertainties associated with different wind measurement techniques (Seneviratne et al., 2012). However, there is increasing evidence for a strengthening wind stress field in the Southern Ocean since the early 1980s from atmospheric reanalyses, satellite observations, and island station data (WGI AR5 Section 3.4.5). Positive trends in wave height have been detected in the Northeast Atlantic over the 1958–2002 period based on reanalyses and ship observations and in the Southern Ocean between 1985 and 2008 based on satellite data (*medium confidence*) (WGI AR5 Section 3.4.6; see Table 5-2).

Projected changes in mean and extreme winds and waves were assigned *low confidence* (Seneviratne et al., 2012) owing to limited studies. Although there has been an increase in studies addressing future wave climate change (Hemer et al., 2013), generally *low confidence* remains in projected wave climate change (except for *medium confidence* over the Southern Ocean), and this is due to uncertainties in future winds, particularly those associated with storms (see WGI AR5 Section 13.7).

5.3.3.4. Sea Surface Temperature

Sea surface temperature (SST) has significantly warmed during the past 30 years along more than 70% of the world's coastlines, with highly heterogeneous rates of change both spatially and seasonally (Lima and Wethey, 2012). The average rate is 0.18 ± 0.16°C per decade and the average change in seasonal timing was -3.3 ± 4.4 days per decade. These values are larger than in the global ocean where the average of change is 0.11 [0.09 to 0.13]°C per decade in the upper 75 m of the ocean during the 1971–2010 period (WGI AR5 Section 3.2.2) and the seasonal shift is -2.3 days per decade (Lima and Wethey, 2012). Extreme events have also been reported. For example, the record high ocean temperatures along the western Australian coast during the austral summer of 2010/2011, with nearshore temperatures peaking at about 5°C above average, were unprecedented (Pearce and Feng, 2013). In summary, positive trends in coastal SSTs are seen on the majority of coastlines, and the rate of rise along coastlines is higher on average than the oceans (*high confidence*). Based on projected temperature increases there is *high confidence* that positive coastal SST trends will continue.

5.3.3.5. Ocean Acidification

Anthropogenic ocean acidification refers to the changes in the carbonate chemistry primarily due to the uptake of atmospheric CO_2 (Box CC-OA). Seawater pH exhibits a much larger spatial and temporal variability in coastal waters compared to open ocean owing to the variable contribution of processes other than CO_2 uptake (Duarte et al., 2013a) such as upwelling intensity (Feely et al., 2008; Box CC-UP), deposition of atmospheric nitrogen and sulfur (Doney et al., 2007), carbonate chemistry of riverine waters (Salisbury et al., 2008; Aufdenkampe et al., 2011), as well as inputs of nutrients and organic matter (Borges, 2011; Cai et al., 2011). For example, pH (NBS scale) ranges from 6 to 9 in 24 estuaries (Borges and Abril, 2011) and short-term (hours to weeks) changes of up to 0.5 pH units are not unusual in coastal ecosystems (Hofmann et al., 2011).

Few high-quality ocean acidification time series exceed 5 years in the coastal ocean (Wootton et al., 2008; Provoost et al., 2010; Waldbusser et al., 2010). Some exhibit considerable differences compared to open ocean stations, illustrating that anthropogenic ocean acidification can be lessened or enhanced by processes such as primary production, respiration, and calcification (Borges and Gypens, 2010; Kleypas et al., 2011).

Under the IS92a CO_2 emission scenario, the global pH (total scale) of coastal waters has been projected to decrease from about 8.16 in the year 1850 to 7.83 in 2100 (Lerman et al., 2011) but with considerable spatial variability. For example, using the same CO_2 emission scenario, Cai et al. (2011) projected an overall decline of pH in the Northern Gulf of Mexico of 0.74 over the same period, a value that is much greater than that of the open ocean (Box CC-OA).

To summarize, seawater pH exhibits considerable temporal and spatial variability in coastal areas compared to open ocean owing to additional natural and human influences (*very high confidence*). Coastal acidification is projected to continue but with large and uncertain regional and local variations (*high confidence*).

5.3.3.6. Freshwater Input

Changes in river runoff arise from changes in climate drivers such as precipitation, complex interactions between changing levels of CO_2, plant physiology, and, consequently, evapotranspiration (e.g., Gedney et al., 2006; Betts et al., 2007) as well as human drivers such as land use change, water withdrawal, dam building, and other engineered modifications to waterways (see more detailed discussion in Chapter 3).

An assessment of runoff trends in 925 of the world's largest ocean-reaching rivers, which account for about 73% of global total runoff, indicates that from 1948–2004 statistically significant trends were present in only one-third of the top 200 rivers and, of these, two-thirds exhibited downward trends and one-third upward trends (Dai et al., 2009). While precipitation changes dominate freshwater flows, decreasing trends in river discharges may be further enhanced as a result of human pressures (Dai et al., 2009; Section 3.2.3).

Average annual runoff is generally projected to increase at high latitudes and in the wet tropics and to decrease in most dry tropical regions (Section 3.4.5). Shifts to earlier peak flows are also projected in areas affected by snowmelt (Adam et al, 2009). However, there are some regions where there is considerable uncertainty in the magnitude and direction of change, specifically South Asia and large parts of South America. Both the patterns of change and the uncertainty are largely driven by projected changes in precipitation.

To summarize, there is *medium confidence* (*limited evidence*, *high agreement*) in a net declining trend in freshwater input globally, although large regional variability exists. Trends are dominated by precipitation changes although human pressures on water supply may enhance downward trends (*medium confidence*). Uncertainty in future changes in runoff is linked to precipitation uncertainty. Runoff is generally projected to increase in high latitudes with earlier peak flows and in the wet tropics and decrease in other tropical regions, however, with large uncertainty (*medium confidence*).

5.3.4. Human-Related Drivers

Coastal systems are subject to a wide range of human-related or anthropogenic drivers (e.g., Crain et al., 2009) that interact with climate-related drivers and confound efforts to attribute impacts to climate change. Some of the major terrestrially based human drivers that directly or indirectly cause changes are briefly reviewed. Related drivers in the marine environment are discussed in Sections 6.4 and 30.6.

5.3.4.1. Socioeconomic Development

Socioeconomic development (SED) drives coastal impacts in several ways. SED influences the number of people and the value of assets exposed to coastal hazards. Since AR4, a number of studies have estimated the influence of future sea level rise and associated hazards on coastal population and assets. Although these estimates are subject to uncertainties associated with global elevation and population data sets (Lichter et al., 2011; Mondal and Tatem, 2012), all the studies indicate high and growing exposure of low-lying coastal areas. The Low Elevation Coastal Zone (LECZ) constitutes 2% of the world's land area but contains 10% of the world's population (600 million) and 13% of the world's urban population (360 million), based on year 2000 estimates (McGranahan et al., 2007). About 65% of the world's cities with populations of greater than 5 million are located in the LECZ (McGranahan et al., 2007). The global population exposed to the 1-in-100-year extreme sea level (i.e., the sea level that has a 1% chance of being exceeded every year) has increased by 95% from 1970 to 2010, with about 270 million people and US$13 trillion worth of assets being exposed to the 1-in-100-year extreme sea level in 2010 (Jongman et al., 2012). In 2002, about US$1.9 trillion worth of assets below the 1-in-100-year extreme sea level were concentrated in the following 10 port cities: Miami (USA), New York-Newark (USA), New Orleans (USA), Osaka-Kobe (Japan), Tokyo (Japan), Amsterdam (Netherlands), Rotterdam (Netherlands), Nagoya (Japan), Virginia Beach (USA), and Guangzhou (China) (Hanson et al., 2011). Compared to other regions, Asia exhibits the greatest exposure in terms of population and assets (Jongman et al., 2012).

For many locations, population and assets exposure is growing faster than the national average trends owing to coastward migration, coastal industrialization, and urbanization (e.g., McGranahan et al., 2007; Seto, 2011; Smith, 2011; see also Chapter 8; *high confidence*). Coastal net migration has largely taken place in flood- and cyclone-prone areas, which poses a challenge for adaptation (de Sherbinin et al., 2011). These processes and associated land use changes are driven by a combination of many social, economic, and institutional factors including taxes, subsidies, insurance schemes, aesthetic and recreational attractiveness of the coast, and increased mobility (Bagstad et al., 2007; Palmer et al., 2011). In China, the country with the largest exposed population, urbanization and land reclamation are the major drivers of coastal land use change (Zhu et al., 2012). Although coastal migration is expected to continue in the coming decades, it is difficult to capture this process in global scenarios, as the drivers of migration and urbanization are complex and variable (Black et al., 2011).

SED also influences the capacity to adapt. Poor people living in urban informal settlements, of which there are about 1 billion worldwide, are particularly vulnerable to weather and climate impacts (de Sherbinin et al., 2011; Handmer et al., 2012). The top five nations classified by population in coastal low-lying areas are developing and newly industrialized countries: Bangladesh, China, Vietnam, India, and Indonesia (McGranahan et al., 2007; Bollman et al., 2010; Jongman et al., 2012). SED and associated land reclamation are also major drivers of the destruction of coastal wetlands, which also makes human settlements more vulnerable because wetlands act as natural buffers reducing wave and storm impacts on the coast (e.g., Crain et al., 2009; Shepard et al., 2011; Arkema et al., 2013; Duarte et al., 2013b). Finally, socioeconomic development is expected to exacerbate further a number of human pressures on coastal systems related to nutrient loads, hypoxia, and sediment delivery, which is discussed in the following subsections.

5.3.4.2. Nutrients

Increased river nutrient (nitrogen, phosphorus) loads to coasts in many regions are observed, and simulated by regional and global models (Alexander et al., 2008; Seitzinger et al., 2010). Anthropogenic global loads of dissolved inorganic nutrients (DIN, DIP) are two to three times larger than those of natural sources (Seitzinger et al., 2010), causing coastal ecosystem degradation (Sections 5.3.4.3, 5.4.2.6). Large variations exist in magnitude and relative sources of nutrient loads. Anthropogenic sources are related primarily to fertilizer use in agriculture and fossil fuel emissions (NO_x) (Galloway et al., 2004; Bouwman et al., 2009).
Future trends depend on measures available to optimize nutrient use in crop production and minimize loss to rivers from agriculture (crop, livestock), sewage, and NO_x emissions. In scenarios with little emphasis on nutrient management, global nutrient discharge increases (DIN 29%, DIP 64%) between 2000 and 2050 (Seitzinger et al., 2010). With ambitious nutrient management, global DIN loads decrease slightly and DIP increases (35%). Climate change is projected to change water runoff (Chapter 3) that influences river nutrient loads. Studies of climate change effects related to increased watershed nutrient sources are needed. In summary, nutrient loads have increased in many world regions (*high confidence*); future increases will depend largely on nutrient management practices (*medium confidence*).

5.3.4.3. Hypoxia

The presence of excessive nutrients in coastal waters, which causes eutrophication and the subsequent decomposition of organic matter, is the primary cause of decreased oxygen concentration (hypoxia). Globally, upwelling of low oxygen waters (e.g., Grantham et al., 2004) and ocean warming, which decreases the solubility of oxygen in seawater (Shaffer et al., 2009), are secondary drivers but can be locally important. The oxygen decline rate is greater in coastal waters than in the open ocean (Gilbert et al., 2010). Hypoxia poses a serious threat to marine life, which is exacerbated when combined with elevated temperature (Vaquer-Sunyer and Duarte, 2011; see also Section 6.3.3). The number of so-called "dead zones" has approximately doubled each decade since 1960 (Diaz and Rosenberg, 2008). Fishery catches from these areas are generally lower than predicted from nutrient loading alone (Breitburg et al., 2009). Although non-climate anthropogenic factors are responsible for virtually all hypoxia in estuaries and inner continental shelves, climate drivers such as ocean warming, altered hydrological cycles, and coastal current shifts and changes in upwellings may interact with eutrophication in the next decades (Rabalais et al., 2010; Meire et al., 2013; *high confidence*).

5.3.4.4. Sediment Delivery

Human activities in drainage basins and coastal plains have impacted the coastal zone by changing the delivery of sediment to the coast. Sediment trapping behind dams, water diversion for irrigation, and sand and gravel mining in river channels all contribute to decrease sediment delivery, whereas soil erosion due to land use changes helps increase it (Syvitski, 2008; Walling, 2006). It is estimated that the global discharge of riverine sediment was 16 to 19 Gt yr^{-1} in the 1950s before widespread dam construction (e.g., Syvitski et al., 2005; Milliman and Farnsworth, 2011) and it has decreased to 12 to 13 Gt yr^{-1} (Syvitski and Kettner, 2011). Out of 145 major rivers with mostly more than 25 years of record, only seven showed evidence of an increase in sediment flux while 68 showed significant downward trends (Walling and Fang, 2003). The number of dams has increased continuously and their distribution has expanded globally. As of early 2011, the world has an estimated 16.7 million reservoirs larger than 0.01 ha (Lehner et al., 2011). Globally, 34 rivers with drainage basins of 19 million km^2 in total show a 75% reduction in sediment discharge over the past 50 years (Milliman and Farnsworth, 2011). Reservoir trapping of sediments is estimated globally as 3.6 Gt yr^{-1} to more than 5 Gt yr^{-1} (Syvitski et al., 2005; Milliman and Farnsworth, 2011; Walling, 2012). Human pressure is the main driver of the observed declining trend in sediment delivery to the coast (*high agreement*).

5.4. Impacts, Vulnerabilities, and Risks

5.4.1. Introduction

This subsection briefly introduces the diverse approaches and methods applied in the literature on coastal impact, vulnerability, and risk. The following subsections then assess this literature related to coastal natural systems (Section 5.4.2) and coastal human systems (Section 5.4.3). Much of this literature focuses on RSLR and extreme sea level events as the main drivers. The main biophysical impacts of this driver are increasing flood damage, dry-land loss due to submergence and erosion, wetland loss and change, saltwater intrusion into surface and ground water, and rising water tables and impeded drainage (Table 5-3).

Impacts and risks are assessed using a wide variety of approaches from the local to global scale. Sea level rise exposure approaches are applied at all scales to assess values exposed to sea level rise (e.g., people, assets, ecosystems, or geomorphological units). Submergence exposure approaches assess exposure to permanent inundation under a given sea level rise (e.g., Dasgupta et al., 2009; Boateng, 2012) whereas flood exposure approaches assess exposure to temporary inundation during a coastal flood event by combining the extreme water level of the flood event with a given level of sea level rise (e.g., Dasgupta et al., 2011; Kebede and Nicholls, 2012).

Indicator-based approaches are also used at all scales to aggregate data on the current state of the coastal systems into vulnerability indices (Gornitz, 1991; Hinkel, 2011), based on either biophysical exposure or hazard variables (e.g., Bosom and Jimenez, 2011; Yin et al., 2012), socioeconomic variables representing a social group's capacity to adapt (e.g., Cinner et al., 2012), or both kinds of variables (e.g., Bjarnadottir et al., 2011; Li and Li, 2011; Yoo et al., 2011).

At local scales (<100 km coastal length), process-based models are applied to assess flooding, erosion, and wetland impacts. Approaches include assessments of flood damage of single extreme water level events using numerical inundation models (e.g., Lewis et al., 2011; Xia et al., 2011). Erosion impacts are assessed using either numerical morphodynamic models (e.g., Jiménez et al., 2009; Ranasinghe et al., 2012) or simple geometric profile relationships such as the Bruun Rule (Bruun, 1962). For ecosystem impacts ecological landscape simulation models are used to predict habitat change due to sea level rise and other factors (e.g., Costanza et al., 1990).

At regional to global scales, numerical process-based models are not available for assessing the impacts of RSLR and extreme sea level events due to data and computational limits. Global scale assessments of coastal impacts have been conducted with the models Climate Framework for Uncertainty, Negotiation and Distribution (FUND) and Dynamic and Interactive Coastal Vulnerability Assessment (DIVA). FUND is an integrated assessment model with a coastal impact component that includes country-level cost functions for dry-land loss, wetland loss, forced migration, and dike construction (Tol, 2002). DIVA is a dedicated coastal impact model employing subnational coastal data (Vafeidis et al., 2008) and considering additional impacts such as coastal flooding and erosion as well as adaptation in terms of protection via dikes and nourishment (Hinkel and Klein, 2009). DIVA assesses coastal flood risk based on hydrologically connected elevation and extreme water level distributions

Frequently Asked Questions

FAQ 5.1 | How does climate change affect coastal marine ecosystems?

The major climate-related drivers on marine coastal ecosystems are sea level rise, ocean warming, and ocean acidification.

Rising sea level impacts marine ecosystems by drowning some plants and animals as well as by inducing changes of parameters such as available light, salinity, and temperature. The impact of sea level is related mostly to the capacity of animals (e.g., corals) and plants (e.g., mangroves) to keep up with the vertical rise of the sea. Mangroves and coastal wetlands can be sensitive to these shifts and could leak some of their stored compounds, adding to the atmospheric supply of these greenhouse gases.

Warmer temperatures have direct impacts on species adjusted to specific and sometimes narrow temperature ranges. They raise the metabolism of species exposed to the higher temperatures and can be fatal to those already living at the upper end of their temperature range. Warmer temperatures cause coral bleaching, which weakens those animals and makes them vulnerable to mortality. The geographical distribution of many species of marine plants and animals shifts towards the poles in response to warmer temperatures.

When atmospheric carbon dioxide is absorbed into the ocean, it reacts to produce carbonic acid, which increases the acidity of seawater and diminishes the amount of a key building block (carbonate) used by marine 'calcifiers' such as shellfish and corals to make their shells and skeletons and may ultimately weaken or dissolve them. Ocean acidification has a number of other impacts, many of which are still poorly understood.

Table 5-3 | Main impacts of relative sea level rise. Source: Adapted from Nicholls et al. (2010).

Biophysical impacts of relative sea level rise	Other climate-related drivers	Other human drivers
Dryland loss due to erosion	Sediment supply, wave and storm climate	Activities altering sediment supply (e.g., sand mining)
Dryland loss due to submergence	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Wetland loss and change	Sediment supply, CO_2 fertilization	Sediment supply, migration space, direct destruction
Increased flood damage through extreme sea level events (storm surges, tropical cyclones, etc.)	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Saltwater intrusion into surface waters (backwater effect)	Runoff	Catchment management and land use (e.g., sand mining and dretching)
Saltwater intrusion into groundwaters leading to rising water tables and impeded drainage	Precipitation	Land use, aquifer use

(Hinkel et al., 2013) and erosion based on a combination of the Bruun Rule and a simplified version of the Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast (ASMITA) model for tidal basins (Nicholls et al., 2011). The results of these models are discussed in Sections 5.4.3.1 and 5.5.5.

For impacts on natural systems, the key climate-related drivers considered are temperature, ocean acidification, and sea level. A variety of approaches are applied including field observations of ecosystem features (e.g., biodiversity, reproduction) and functioning (e.g., calcification, primary production), remote sensing (e.g., extent of coral bleaching, surface area of vegetated habitats), and perturbation experiments in the laboratory and in the field.

5.4.2. Natural Systems

Coastal ecosystems are experiencing large cumulative impacts related to human activities (Halpern et al., 2008) arising from both land- and ocean-based anthropogenic drivers. Anthropogenic drivers associated with global climate change are distributed widely and are an important component of cumulative impacts experienced by coastal ecosystems. There is no wetland, mangrove, estuary, rocky shore, or coral reef that is not exhibiting some degree of impact. Overexploitation and habitat destruction are often the primary causes of historical changes in coastal systems leading to declines in diversity, structure, and functioning (Lotze et al., 2006). Further, extreme climate events generate changes to both the mean and the variance of climatic variables over ecological time scales.

5.4.2.1. Beaches, Barriers, and Sand Dunes

Beaches, barriers, and sand dunes are about half as common as rocky coasts (Bird, 2000; Davis and FitzGerald, 2004) and often exhibit distinct and seasonal changes. Owing to their aesthetic qualities, they are highly valued for recreation and residences.

5.4.2.1.1. Observed impacts

Globally, beaches and dunes have in general undergone net erosion over the past century or longer (e.g., for an overview, see Bird, 2000). A number of studies have investigated shoreline change by comparing historical maps and imagery, available since about the mid-19th century with more recent maps and imagery to quantify combined climate and non-climate changes. For example, along the U.S. Mid-Atlantic and New England coasts the long-term rate of erosion, based on 21,184 transects equally spaced along more than 1000 km of coast, is 0.5 ± 0.09 m yr^{-1}, with 65% of transects showing net erosion (Hapke et al., 2011). A similar study by Webb and Kench (2010) in the central Pacific utilized historical aerial photographs and satellite images to show physical changes in 27 islets located in four atolls over a 19- to 61-year period. The analysis highlighted the dynamic nature of sea level rise response in the recent past, with physical changes in shoreline progradation and displacement influencing whether the island area increased (46%), remained stable (46%), or decreased (14%).

Attributing shoreline changes to climate change is still difficult owing to the multiple natural and anthropogenic drivers contributing to coastal erosion. For example, rotation of pocket beaches (i.e., where one end of the beach accretes while the other erodes and then the pattern reverses) in southeast Australia is closely related to interannual changes in swell direction (Harley et al., 2010). Additional processes, unrelated to climate change, that contribute to coastal change include dams capturing fluvial sand (e.g., in Morocco; Chaibi and Sedrati, 2009). Statistically linking sea level rise to observed magnitudes of beach erosion has had some success, although the coastal sea level change signal is often small when compared to other processes (e.g., Leatherman et al., 2000a,b; Sallenger et al., 2000; Zhang et al., 2004). A Bayesian network incorporating a variety of factors affecting coastal change, including RSLR, has been successful in hindcasting shoreline change, and can be used to evaluate the probability of future shoreline change (Gutierrez et al., 2011).

While some coastal systems may be able to undergo landward retreat under rising sea levels, others will experience coastal squeeze, which occurs when an eroding shoreline approaches hard, immobile structures such as seawalls or resistant natural cliffs. In these instances the beaches will narrow owing to the resulting sediment deficit and produce adverse impacts such as habitat destruction, impacting the survivability of a variety of organisms (Jackson and McIlvenny, 2011). With such a manifestation of coastal squeeze, sand dunes will ultimately be removed as the beach erodes and narrows. Extreme storms can erode and completely remove dunes, degrading land elevations and exposing them to inundation and further change if recovery does not occur before the next storm (Plant et al., 2010). Even in the absence of hard obstructions, barrier island erosion and narrowing can occur, as a result of rising sea level and recurrent storms, as in the Chandeleur Islands and Isles Dernieres, Louisiana, USA (Penland et al., 2005).

5.4.2.1.2. Projected impacts

With projected GMSLR (see Section 5.3.3), inundation and erosion may become detectable and progressively important. In the first instance,

Frequently Asked Questions

FAQ 5.2 | How is climate change influencing coastal erosion?

Coastal erosion is influenced by many factors: sea level, currents, winds, and waves (especially during storms, which add energy to these effects). Erosion of river deltas is also influenced by precipitation patterns inland which change patterns of freshwater input, runoff, and sediment delivery from upstream. All of these components of coastal erosion are impacted by climate change.

Based on the simplest model, a rise in mean sea level usually causes the shoreline to recede inland due to coastal erosion. Increasing wave heights can cause coastal sand bars to move away from the shore and out to sea. High storm surges (sea levels raised by storm winds and atmospheric pressure) also tend to move coastal sand offshore. Higher waves and surges increase the probability that coastal sand barriers and dunes will be over-washed or breached. More energetic and/or frequent storms exacerbate all these effects.

Changes in wave direction caused by shifting climate may produce movement of sand and sediment to different places on the shore, changing subsequent patterns of erosion.

the impacts will be apparent through sea level rise which, combined with storm surge, will make extreme water levels higher and more frequent and therefore enable greater attack on beaches and dunes (Tebaldi et al., 2012).

The Bruun rule (a simple rule based on the assumption that to maintain an equilibrium cross-shore profile under rising sea levels, the coastline will move landwards a distance of approximately 100 times the vertical sea level rise; Bruun, 1962) has been used by many researchers to calculate erosion by sea level rise. However, there is disagreement about whether the Bruun rule is appropriate (Cooper and Pilkey, 2004; Woodroffe and Murray-Wallace, 2012), and how to calculate the amount of retreat remains controversial (Gutierrez et al., 2011; Ranasinghe et al., 2012). An increase in storm intensity and ocean swell may accelerate erosion of beaches, barriers, and dunes, although in some places beach response to sea level rise could be more complex than just a simple retreat (Irish et al., 2010).

Coastal squeeze is expected to accelerate with a rising sea level. In many locations, finding sufficient sand to rebuild beaches and dunes artificially will become increasingly difficult and expensive as present supplies near project sites are depleted (*high confidence*). New generation models are emerging to estimate the costs of saving oceanfront homes through beach nourishment relative to the structures cost (McNamara et al., 2011). In the absence of adaptation measures, beaches and sand dunes currently affected by erosion will continue to be affected under increasing sea levels (*high confidence*).

5.4.2.2. Rocky Coasts

Rocky coasts with shore platforms form about three-fourths of the world's coasts (Davis and FitzGerald, 2004; Jackson and McIlvenny, 2011) and are characterized by very strong environmental gradients, especially in the intertidal zone where both marine and atmospheric climate regime changes can pose challenges.

5.4.2.2.1. Observed impacts

Cliffs and platforms are erosional features and any change that increases the efficiency of processes acting on them, such as RSLR, storminess, wave energy, and weathering regimes, increases erosion (Naylor et al., 2010). Their responses vary, owing to different lithology (e.g., hard rock vs. non-lithified soft rock) and profiles (e.g., plunging cliffs or cliffs with shore platforms). Cliffs and platforms have reduced resilience to climate change impacts; once platforms are lowered or cliffs have retreated, it is difficult to rebuild them (Naylor et al., 2010). On the decadal scale, for example, the retreat of soft rock cliffs in East Anglia, UK, has been linked to the North Atlantic Oscillation (NAO) phases with high energetics (Brooks and Spencer, 2013).

Changes in the abundance and distribution of rocky shore animals and algae have long been recognized (Hawkins et al., 2008), and perturbation experiments provide information about environmental limits, acclimation, and adaptation, particularly to changes in temperature (Somero, 2012). The challenge is to attribute the changes to climate-related drivers, human-related drivers, and to natural fluctuations.

The range limits of many intertidal species have shifted by up to 50 km per decade over the past 30 years in the North Pacific and North Atlantic, much faster than most recorded shifts of terrestrial species (Helmuth et al., 2006; Box CC-MB). However, the distribution of some species has not changed in recent decades, which may be due to weak local warming (Rivadeneira and Fernández, 2005) or overriding effects of variables such as timing of low tide; hydrographic features; lack of suitable substrate; poor larval dispersal; and effects of food supply, predation, and competition (Helmuth et al., 2002, 2006; Poloczanska et al., 2011).

The dramatic decline of biodiversity in mussel beds of the Californian coast has been attributed to large-scale processes associated with climate-related drivers (59% mean loss in species richness, comparing 2002 to historical data (1960s to 1970s); Smith et al., 2006) (*high* *confidence*). Warming reduced predator-free space on rocky shores, leading to a decrease of the vertical extent of mussel beds by 51% in 52 years in the Salish Sea, and to the disappearance of reproductive populations of mussels (Harley, 2011). Unusually high air or water temperature led to mass mortalities, for example, of mussels on the California coast (Harley, 2008) and gorgonians in the northwestern Mediterranean (Garrabou et al., 2009).

Rocky shores are one of the few ecosystems for which field evidence of the effects of ocean acidification is available. Observational and modeling analysis have shown that the community structure of a site of the northeast Pacific shifted from a mussel to an algal-barnacle dominated community between 2000 and 2008 (Wootton et al., 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012).

5.4.2.2.2. Projected impacts

Modeled relationships suggest that soft-rock recession rates depends on the relative change in sea level rise while cliff retreat depends both on total elevation change of sea level and on the rate of sea level rise (Ashton et al., 2011). In a modeling study, Trenhaile (2010) found sea level rise to trigger faster rates of cliff recession, especially in coasts that are already retreating fast. In addition, based on modeling cliff dynamics with contemporary and historic data of soft cliff retreat along Suffolk Coast, UK, rapid retreat is associated with accelerating sea level rise (Brooks and Spencer, 2013). However, coasts currently retreating slowly would experience the largest proportional increase in retreat rates. Increases in storminess have smaller effects on rocky shores (Dawson et al., 2009; Trenhaile, 2011).

Few projections of the effect of climate change on rocky shores have considered the effects of direct and indirect species interactions (Poloczanska et al., 2008; Harley, 2011) and the effects of multiple drivers (Helmuth et al., 2006). The abundance and distribution of rocky shore species will continue to change in a warming world (*high confidence*). For example, the long-term consequences of ocean warming on mussel beds of the northeast Pacific are both positive (increased growth) and negative (increased susceptibility to stress and of exposure to predation) (Smith et al., 2006; Menge et al., 2008; *medium confidence*). Extrapolations of ecosystem change based on temperature-focused studies alone are likely to be conservative, as hypoxia (Grantham et al., 2004) or ocean acidification (Feely et al., 2008) are also known to occur in this region.

Observations performed near natural CO_2 vents in the Mediterranean Sea show that diversity, biomass, and trophic complexity of rocky shore communities will decrease at future pH levels (Barry et al., 2011; Kroeker et al., 2011; *high confidence*). An abundant food supply appears to enable mussels of the Baltic Sea to tolerate low pH (Thomsen et al., 2010, 2013) at the cost of increased energy expenditure. Model projections that include the interactive effects of ocean warming and acidification suggest that a population of barnacle of the English Channel will become extinct 10 years earlier than it would with warming alone (Findlay et al., 2010; *medium confidence*). Ocean acidification may also exacerbate mass mortality events in the Mediterranean Sea (Rodolfo-Metalpa et al., 2011; *limited evidence*, *medium agreement*).

In summary, rocky shores are among the better-understood coastal ecosystems in terms of potential impacts of climate variability and change. The most prominent effects are range shifts of species in response to ocean warming (*high confidence*) and changes in species distribution and abundance (*high confidence*) mostly in relation to ocean warming and acidification.

5.4.2.3. Wetlands and Seagrass Beds

Vegetated coastal habitats and coastal wetlands (mangrove forests, salt marshes, seagrass meadows, and macroalgal beds) extend from the intertidal to the subtidal areas in coastal areas, where they form key ecosystems.

5.4.2.3.1. Observed impacts

Vegetated coastal habitats are declining globally (Duarte et al., 2005), rendering shorelines more vulnerable to erosion due to increased sea level rise and increased wave action (e.g., Alongi, 2008) and leading to the loss of carbon stored in sediments. Together, the loss of coastal wetlands and seagrass meadows results in the release of 0.04 to 0.28 PgC annually from organic deposits (Pendleton et al., 2012). Recognition of the important consequences of the losses of these habitats for coastal protection and carbon burial (Duarte et al., 2013a) has led to large-scale reforestation efforts in some nations (e.g., Thailand, India, Vietnam).

The response of saltmarshes to sea level rise involves landward migration of salt-marsh vegetation zones, submergence at lower elevations, and drowning of interior marshes. Ocean warming is leading to range shifts in vegetated coastal habitats. The poleward limit of mangrove forests is generally set by the 20ºC mean winter isotherm (Duke et al., 1998). Accordingly, migration of the isotherm with climate change (Burrows et al., 2011) should lead to a poleward expansion of mangrove forests, as observed in the Gulf of Mexico (Perry and Mendelssohn, 2009; Comeaux et al., 2011; Raabe et al., 2012) and New Zealand (Stokes et al., 2010), leading to increased sediment accretion (*medium confidence*).

Seagrass meadows are already under stress due to climate change (*high confidence*), particularly where maximum temperatures already approach their physiological limit. Heat waves lead to widespread seagrass mortality, as documented for *Zostera* species in the Atlantic (Reusch et al., 2005) and *Posidonia* meadows in the Mediterranean Sea (Marbà and Duarte, 2010) and Australia (Rasheed and Unsworth, 2011; *high confidence*). Warming also favors flowering of *P. oceanica* (Diaz-Almela et al., 2007), but the increased recruitment rate is insufficient to compensate for the losses resulting from elevated temperatures (Diaz-Almela et al., 2009).

Kelp forests have been reported to decline in temperate areas in both hemispheres (Fernández, 2011; Johnson et al., 2011; Wernberg et al., 2011a,b), a loss involving climate change (*high confidence*). Decline in kelp populations attributed to ocean warming has been reported in southern Australia (Johnson et al., 2011; Wernberg et al., 2011a,b) and the North Coast of Spain (Fernández, 2011). The spread of subtropical invasive macroalgal species may be facilitated by climate change, adding to the stresses experienced by temperate seagrass meadows due to ocean warming (*medium evidence*, *high agreement*).

5.4.2.3.2. Projected impacts

Ocean acidification (Section 5.3.3.5; Box CC-OA) is expected to enhance the production of seagrass, macroalgae, salt-marsh plants, and mangrove trees through the fertilization effect of CO_2 (Hemminga and Duarte, 2000; Wu et al., 2008; McKee et al., 2012; *high confidence*). Increased CO_2 concentrations may have already increased seagrass photosynthetic rates by 20% (Hemminga and Duarte, 2000; Hendriks et al., 2010; *limited evidence, high agreement*).

Coupling of downscaled model projections using the SRES A1B scenario in the western Mediterranean with relationships between mortality rates and maximum seawater temperature led Jordá et al. (2012) to conclude that seagrass meadows may become functionally extinct by 2050–2060 (*high confidence*). Poleward range shifts in vegetated coastal habitats are expected to continue with climate change (*high confidence*).

Although elevated CO_2 and ocean acidification are expected to increase productivity of vegetated coastal habitats in the future, there is *limited evidence* that elevated CO_2 will increase seagrass survival or resistance to warming (Alexandre et al., 2012; Jordá et al., 2012).

Coastal wetlands and seagrass meadows experience coastal squeeze in urbanized coastlines, with no opportunity to migrate inland with rising sea levels. However, increased CO_2 and warming can stimulate marsh elevation gain, counterbalancing moderate increases in sea level rise rates (Langley et al., 2009; Kirwan and Mudd, 2012). Climate change is expected to increase carbon burial rates on salt marshes during the first half of the 21st century, provided sufficient sediment supply, with carbon-climate feedbacks diminishing over time (Kirwan and Mudd, 2012; *medium confidence*).

In summary, climate change will contribute to the continued decline in the extent of seagrasses and kelps in the temperate zone (*medium confidence*) and the range of seagrasses, mangroves, and kelp in the Northern Hemisphere will expand poleward (*high confidence*). The limited positive impact of warming and increased CO_2 on vegetated ecosystems will be insufficient to compensate the decline of their extent resulting from other human drivers such as land use change (*very high confidence*).

5.4.2.4. Coral Reefs

Coral reefs are shallow-water ecosystems made of calcium carbonate secreted by reef-building corals and algae. They are among the most diverse ecosystems and provide key services to humans (Box CC-CR).

5.4.2.4.1. Observed impacts

Mass coral bleaching coincided with positive temperature anomalies over the past 30 years, sometimes followed by mass mortality (Kleypas et al., 2008; *very high confidence*). More than 80% of corals bleached during the 2005 event in the Caribbean and more than 40% died (Eakin et al., 2010). Bleaching events and their recovery are variable in time and space: 7% of the reef locations exhibited at least one bleaching between 1985 and 1994 compared to 38% in the 1995–2004 period, most of which occurred during the 1997–98 El Niño event (Figure 5-3). Recovery from the 1998 global bleaching event was generally variable in the Indian Ocean, absent in the western Atlantic, and no clear trends elsewhere (Baker et al., 2008). Warming has caused a poleward range expansion of some corals (Greenstein and Pandolfi, 2008; Yamano et al., 2011; *high confidence*).

Persistence of coral reefs depends on the balance between the production and erosion of calcium carbonate and on coral settlement, both of which are affected by ocean acidification (Section 5.3.3.5; Box CC-OA). Experimental data show that ocean acidification generally decreases calcification (Andersson et al., 2011; Kroeker et al., 2013) and promotes dissolution of calcium carbonate and bioerosion (Tribollet et al., 2009; Wisshak et al., 2012), leading to poorly cemented reefs (Manzello et al., 2008); it also negatively affects early life history stages, which could reduce the number of larval settlers (Albright, 2011).

Coral cover and calcification have decreased in recent decades (e.g., Gardner et al., 2003; De'ath et al., 2009, 2012; Manzello, 2010; Box CC-CR; *very high confidence*) but attribution to climate-related and human-related drivers is difficult. Globally, the primary climate-related driver appears to be ocean warming rather than ocean acidification, cyclonic activity, and changes in freshwater input (Cooper et al., 2012; De'ath et al., 2012; *medium confidence*). Sea level rise also controls reef growth but, within the uncertainties of past sea level rise and coral reef growth, most coral reefs seem to have kept pace with the recent sea level rise (Buddemeier and Smith, 1988; Brown et al., 2011).

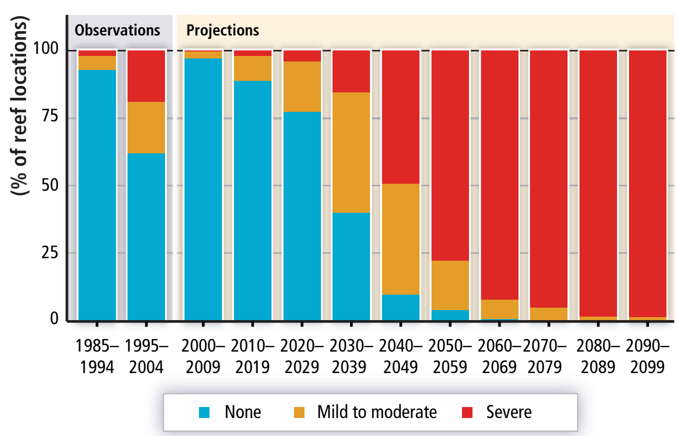

Figure 5-3 | Percent of reef locations (1° × 1° grid cells which have at least one reef) that experience no bleaching, at least one mild bleaching event, or at least one severe bleaching event for each decade. Observed bleaching events are summarized from the ReefBase data set (Kleypas et al., 2008). In the observations, some of the "no bleaching" cells may have experienced bleaching but it was either not observed or not reported. Modeled bleaching events are averages of data from four ensemble runs of the Community Climate System Model version 3 using the Special Report on Emissions Scenarios (SRES) A1B scenario and the standard degree heating month formula (Teneva et al., 2011). The labels of values ≤1% are not shown.

5

5.4.2.4.2. Projected impacts

Coral bleaching and mortality will increase in frequency and magnitude over the next decades (*very high confidence*). Under the A1B CO_2 emission scenario, 99% of the reef locations will experience at least one severe bleaching event between 2090 and 2099 (Figure 5-3), with *limited evidence* and *low agreement* that coral acclimation and/or adaptation will limit this trend (Logan et al., 2014). The onset of annual bleaching event under RCP8.5 is delayed by more than 2 decades in about 23% of reef locations compared to RCP6.0 (van Hooidonk et al., 2013).

Ocean warming and acidification have synergistic effects in several reef-builders (Reynaud et al., 2003; Anthony et al., 2008). They will increase coral mortality, reduce calcification and the strength of calcified organisms, and enhance skeletal dissolution (Manzello et al., 2008; *high confidence*). Reefs will transition from a condition of net accretion to one of net erosion (Andersson and Gledhill, 2013; *high confidence*) and will be more susceptible to breakage. The onset of global dissolution is at an atmospheric CO_2 of 560 ppm (Silverman et al., 2009; *medium confidence*) and dissolution will be widespread in 2100 (RCP8.5 emission scenario, Dove et al., 2013; *medium confidence*). The observed poleward range extension will be limited by ocean acidification (Yara et al., 2012; Couce et al., 2013) and may be followed by equatorial range retractions (Kiessling et al., 2012).

The maximum rate of vertical accretion has been variable regionally during the last deglaciation (about 20 mm yr^{-1}; Dullo, 2005; Montaggioni, 2005) and has not enabled all coral reefs to keep up with sea level rise. Some reefs kept up, even when the eustatic sea level rise exceeded 40 mm yr^{-1} (Camoin et al., 2012). A number of coral reefs could therefore keep up with the maximum rate of sea level rise of 15.1 mm yr^{-1} projected for the end of the century (WGI AR5 Table 13.5; *medium confidence*) but a lower net accretion than during the Holocene (Perry et al., 2013) and increased turbidity (Storlazzi et al., 2011) will weaken this capability (*very high confidence*).

In summary, ocean warming is the primary cause of mass coral bleaching and mortality (*very high confidence*), which, together with ocean acidification, deteriorates the balance between coral reef construction and erosion (*high confidence*). The magnitude of these effects depends on future rates of warming and acidification (*very high confidence*), with a limited moderating role owing to biological acclimation and adaptation (*medium confidence*).

5.4.2.5. Coastal Aquifers

Coastal aquifers are of strategic importance for the water supply of highly populated coastal areas, especially in small islands (Section 29.3).

5.4.2.5.1. Observed impacts

Temperature and evaporation rise, precipitation changes, and extended droughts affecting aquifer recharge can contribute to saltwater intrusion (Section 3.2.4). Rising sea levels and overwash from waves or storm surge are also relevant, especially in low-lying areas and islands (Terry and Falkland, 2010; White and Falkland, 2010; see also Section 29.3).

Aquifers on the coasts of the USA have experienced increased levels of salinity largely due to excessive water extraction (Barlow and Reichard, 2010). Natural drivers combined with over-extraction, pollution, mining, and erosion compound groundwater supply problems in small islands in the Pacific, Indian, and Atlantic Oceans (White et al., 2007; White and Falkland, 2010). This increased usage of groundwater resources globally has, over the last century, led to a reduction in groundwater quality, including increased salinization (*very high confidence*).

Attribution of saline intrusion to incremental sea level rise is still not sufficiently supported (Rozell and Wong, 2010; White and Falkland 2010). In small islands, observed saltwater intrusion due to flooding and overwash under storm events cannot be attributed to climate change (Section 29.3.2; *limited evidence*, *high agreement*).

5.4.2.5.2. Projected impacts

Available information on projected impacts on coastal aquifers is limited (Section 3.4.6). Rozell and Wong (2010) assessed the impact of rising sea levels on fresh water resources on Shelter Island (USA) for two different combinations of precipitation change and sea level rise. Projected impacts were highly dependent on local conditions. Ferguson and Gleeson (2012) concluded that the direct impact of groundwater extraction in the USA has been and will be much more significant than the impact of a 0.59 m sea level rise by the end of the 21st century under a wide range of hydrogeological conditions and population densities.

Saltwater intrusion is generally a very slow process; as a consequence, reaching equilibrium may take several centuries limiting the reversibility of the process in the near term (Webb and Howard, 2011).

Human-induced pressure will continue to be the main driver for aquifer salinization during the next century (*high confidence*). Changing precipitation, increased storminess, and sea level rise will exacerbate these problems (*limited evidence*, *high agreement*).

5.4.2.6. Estuaries and Lagoons

Coastal lagoons are shallow water bodies separated from the ocean by a barrier and connected at least intermittently to the ocean, while estuaries, where fresh and saltwater mix, are the primary conduit for nutrients, particulates, and organisms from land to the sea.

5.4.2.6.1. Observed impacts

Sediment accumulation in estuaries is high, heterogeneous, and habitat-specific and directly affected by human drivers, such as dredging and canalization, and indirectly via habitat loss, changes in sea level, storminess, and freshwater and sediment supply by rivers (Syvitski et al., 2005; Swanson and Wilson, 2008). Coastal lagoons are also susceptible to alterations of sediment input and erosional processes driven by changes in sea level, precipitation, and storminess (Pickey and Young, 2009). Droughts, floods, and sea level rise impact estuarine circulation, tidal characteristics, suspended matter, and hence turbidity with consequences for biological communities, particularly in microtidal systems. Climate change and habitat modification (e.g., dams and obstructions) impact fish species such as salmon and eels that pass through estuaries (Lassalle and Rochard, 2009).

Enhanced nutrient delivery (Section 5.3.4.3) has resulted in major changes in biogeochemical processes, community structure, metabolic balance, and CO_2 exchange (Howarth et al., 2011; Canuel et al., 2012; Statham, 2012), including enhanced primary production which has affected coastal fishery yield (Nixon, 1982; Savage et al., 2012). Eutrophication has modified the food-web structure (*high confidence*) and led to more intense and long lasting hypoxia (Section 5.3.4.4), more frequent occurrence of harmful algal blooms (Breitburg et al., 2009; Howarth et al., 2011; *medium confidence*), and to enhanced emission of nitrous oxide (de Bie et al., 2002; Kroeze et al., 2010; *high confidence*).

In summary, there is *very high confidence* that humans have impacted lagoons and estuaries.

5.4.2.6.2. Projected impacts

The increase of atmospheric CO_2 levels will reduce the efflux of CO_2 from estuaries (Borges, 2005; Chen and Borges, 2009; *high confidence*). Its impact on the pH of estuarine and lagoon waters will generally be limited because other drivers are usually more important (Section 5.3.3.4 and Box CC-OA; *high confidence*). For example, freshwater flow in the Scheldt estuary was the main factor controlling pH, directly via a decreased supply of dissolved inorganic carbon and total alkalinity, and, indirectly, via decreased input ammonia loadings and lower rates of nitrification (Hofmann et al., 2009).

Changes in sea level and hydrology could affect lagoons and estuaries in multiple ways. Sea level rise will impact sediment redistribution, the partitioning of habitats within estuaries, salinity, tidal range, and submergence periods (Anthony et al., 2009; *high confidence*). Lagoons may shrink because landward migration is restricted due to human occupation or extend due to the drowning of marshes (Anthony et al., 2009; Pilkey and Young, 2009; Stutz and Pilkey, 2011). Salinity, primary production, biodiversity, fisheries, and aquaculture may be impacted by changes in water discharge, withdrawals and precipitation-evaporation balance (Webster and Harris, 2004; Smith et al., 2005; Anthony et al., 2009; Canu et al., 2010). Altered riverine discharge and warming may lead to enhanced thermal and/or salinity stratification of estuaries and lagoons. This has consequences for biogeochemical processes, organism distribution patterns, and frequency and duration of hypoxia (Diaz and Rosenberg, 2008; Rabalais et al., 2009; Hong and Shen, 2012; *medium confidence*). Stronger winds and droughts may reduce the extent, duration, and frequency of estuarine stratification, counteracting the decrease in oxygen concentration (Rabalais et al., 2009; *medium confidence*).

Changes in storm events may also alter the sediment deposition-erosion balance of lagoons and estuaries (Pilkey and Young, 2009), the structure and functioning of biological communities via the transport of communities and/or of their resources, and the underwater light climate (Wetz and Paerl, 2008; Canuel et al., 2012; *medium confidence*). Changes in precipitation extremes and freshwater supply may induce fluctuations in salinity with the associated adverse impacts on biodiversity, benthic macrofauna, and ecosystem functions (Jeppesen et al., 2007; Fujii and Raffaelli, 2008; Levinton et al., 2011; Pollack et al., 2011). Warming may directly affect most biological processes and the trophic status of coastal ecosystems, and higher carbon dioxide emission (Canuel et al., 2012; *limited evidence*, *medium agreement*). Warming may lengthen the duration of phytoplankton production season (Cloern and Jassby, 2008; *medium confidence*).

Any change in the primary production of lagoons might impact fisheries, as primary production and fisheries yield are correlated (Nixon, 1982; *limited evidence*, *medium agreement*). For example, seawater warming and changes in seasonal patterns of precipitations projected in the Venice lagoon, using the SRES A2 emission scenario for the period 2071–2100, may lead to a reduction in plankton production, with a decline of habitat suitability for clam growth and aquaculture (Canu et al., 2010).

Finally, projected changes in climate-related drivers such as warming, storms, sea level, and runoff will interact with non-climate human drivers (e.g., eutrophication, damming) and will have consequences for ecosystem functioning and services of lagoons and estuaries (*high confidence*).

In summary, the primary drivers of change in lagoons and estuaries are human-related rather than climate-related drivers (*very high confidence*). Future changes in climate-related drivers such as warming, acidification, waves, storms, sea level, and runoff will have consequences on the functions and services of ecosystems in lagoons and estuaries (*high confidence*) but the impacts cannot be assessed at the global scale as the key drivers operate at a local to regional scale.

5.4.2.7. Deltas

Characterized by the interplay between rivers, lands, and oceans and influenced by a combination of river, tidal, and wave processes, deltas are coastal complexes that combine natural systems in diverse habitats (e.g., tidal flats, salt marshes, mangroves, beaches, estuaries, low-lying wetlands) and human systems (e.g., houses, agriculture, aquaculture, industry, and transport). They are low-lying coastal landforms formed by riverine sediments in the areas around river mouths, mostly during the last 6000–8000 years of relatively stable sea level and have a population density more than 10 times the world average (Ericson et al., 2006; Foufoula-Georgiou et al., 2011). As low-lying plains, deltas are highly sensitive to changes in sea level. They are subject to climatic impacts from rivers upstream (e.g., freshwater input) and oceans downstream (e.g., sea level changes, waves) as well as within the deltas themselves. At the same time, they are affected by human activities such as land use changes, dam construction, irrigation, mining, extraction of subsurface resources, and urbanization (Nicholls et al., 2007).

5.4.2.7.1. Observed impacts

The combined impact of sediment reduction, RSLR, and land use changes in delta and river management on channels and banks has led to the widespread degradation of deltas (*very high confidence*). The changes of sediment delivery from rivers due to dams, irrigation, and embankments/dikes create an imbalance in sediment budget in the coastal zones. Degradation of beaches, mangroves, tidal flats, and subaqueous delta fronts along deltaic coasts has been reported in many deltas (e.g., Nile and Ebro; Sanchez-Arcilla et al., 1998; Po, Simeoni and Corbau, 2009; Krishna-Godavari, Nageswara Rao et al., 2010; Changjiang, Yang et al., 2011; Huanghe, Chu et al., 1996; *very high confidence*). Deltaic coasts naturally evolve by seaward migration of the shoreline, forming a delta plain. However, decreasing sediment discharge during the last 50 years has decreased the growth of deltaic land, even reversing it in some locations (e.g., Nile, Godavari, Huanghe). Artificial reinforcement of natural levees also has reduced the inter-distributory basin sedimentation in most deltas, resulting in wetland loss.

The major impacts of sea level rise are changes in coastal wetlands, increased coastal flooding, increased coastal erosion, and saltwater intrusion into estuaries and deltas (Mcleod et al., 2010), which are exacerbated by increased human-induced drivers (*very high confidence*). Ground subsidence amplifies these hazards in farms and cities on deltaic plains through RSLR (Day and Giosan, 2008; Mazzotti et al., 2009). RSLR due to subsidence has induced wetland loss and shoreline retreat (e.g., the Mississippi delta; Morton et al., 2005; Chao Phraya delta, Saito et al., 2007; *high confidence*). Episodic events superimpose their effects on these underlying impacts and accelerate land loss (*high confidence*) (e.g., Hurricanes Katrina and Rita in 2005; Barras et al., 2008). To forestall submergence and frequent flooding, many delta cities now depend on a substantial infrastructure for flood defense and water management (Nicholls et al., 2010).

Deltas are impacted by river floods and oceanic storm surges (*very high confidence*). Tropical cyclones are noteworthy for their damages to deltas, for example, the Mississippi delta by Hurricane Katrina in 2005 (Barras et al., 2008), the Irrawaddy delta by Cyclone Nargis in 2008, and the Ganges-Brahmaputra delta by Cyclone Gorky in 1991 and Cyclone Sidr in 2007 (Murray et al., 2012; see also Box CC-TC). A detailed study of 33 deltas around the world found that 85% of them had experienced severe flooding in the past decade, causing the temporary submergence of 260,000 km^2 (Syvitski et al., 2009).

5.4.2.7.2. Projected impacts

The projected natural impacts on deltas under changing global climate are caused mainly by extreme precipitation-induced floods and sea level rise. These will result in increased coastal flooding, decreased wetland areas, increased coastal erosion, and increased salinization of cultivated land and groundwater (McLeod et al., 2010; Day et al., 2011; Box CC-TC; *high confidence*). The surface area of flooding in 33 deltas around the world is estimated to increase by 50% under sea level rise estimations as projected for 2100 by the IPCC AR4 (Syvitski et al., 2009). Non-climatic drivers (e.g., reduction in sediment delivery, subsidence, and land use changes) rather than climatic drivers have affected deltas for the last 50 years (Syvitski, 2008; *very high confidence*). Densely populated deltas are particularly vulnerable owing to further population growth together with the above-described impacts. The impacts beyond 2100 show a more complex and enhanced flood risk on deltas (e.g., Katsman et al., 2011).

In summary, increased human drivers have been primary causes in changes of deltas (e.g., land use, subsidence, coastal erosion) for at least the last 50 years (*very high confidence*). There is *high agreement* that future sea level rise will exacerbate the problems of increased anthropogenic degradation in deltas.

5.4.3. Human Systems

5.4.3.1. Human Settlements

Important direct effects of climate change on coastal settlements include dry-land loss due to erosion and submergence, damage of extreme events (such as wind storms, storm surges, floods, heat extremes, and droughts) on built environments, effects on health (food- and water-borne disease), effects on energy use, effects on water availability and resources, and loss of cultural heritage (Hunt and Watkiss, 2010). Since AR4, a large number of regional, national, and subnational scale studies on coastal impacts have been conducted. These are covered in the respective regional chapters. At the global scale, studies have focused either on exposure to sea level rise or extreme water levels or on the physical impacts of flooding, submergence, and erosion.

5.4.3.1.1. Projected exposure

Coastal flood risks are strongly influenced by the growing exposure of population and assets. The population exposed to the 1-in-100-year coastal flood is projected to increase from about 270 million in 2010 to 350 million in 2050 due to socioeconomic development only (UN medium fertility projections) (Jongman et al., 2012). Population growth, economic growth, and urbanization will be the most important drivers of increased exposure in densely populated areas (Hanson et al., 2011; Seto, 2011; see also Chapter 14; *high confidence*). For 136 port cities above 1 million inhabitants, the number of people exposed to a 1-in-100-year extreme sea level is expected to increase from 39 million in 2005 to 59 million by 2070 through 0.5 m GMSLR alone and to 148 million if socioeconomic development (UN medium population projections) is considered (Hanson et al., 2011). Human-induced subsidence alone is expected to increase the global economic exposure of 136 major port cities by around 14% from 2005 to 2070 although this driver only applies to 36 of the cities (Hanson et al., 2011). As a result of socioeconomic development Asia is expected to continue to have the largest exposed population and sub-Saharan Africa the largest increases in exposure (Dasgupta et al., 2009; Vafeidis et al., 2011; Jongman et al., 2012).

5.4.3.1.2. Projected impacts and risks

Exposure estimates, however, give an incomplete picture of coastal risks to human settlements because they do not consider existing or future adaptation measures that protect the exposed population and assets against coastal hazards (Hallegatte et al., 2013; Hinkel et al., 2013). Although the global potential impacts of coastal flood damage and land loss on human settlements in the 21st century are substantial, these impacts can be reduced considerably through coastal protection (*limited evidence*, *high agreement*). Nicholls et al. (2011) estimate that without

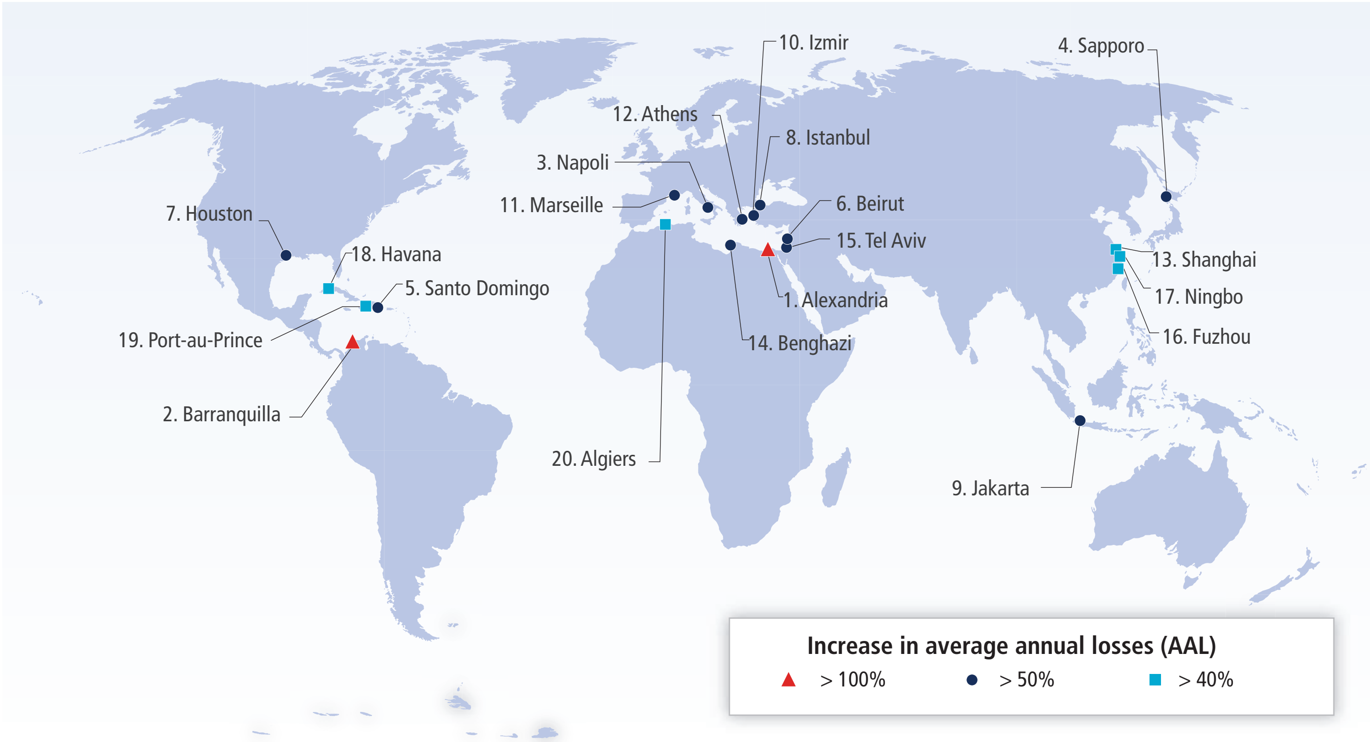

Figure 5-4 | The 20 coastal cities where average annual losses (AALs) increase most (in relative terms in 2050 compared with 2005) in the case of optimistic sea level rise, if adaptation maintains only current defense standards or flood probability (PD) (Hallegatte et al., 2013).

protection 72 to 187 million people would be displaced due to land loss due to submergence and erosion by 2100 assuming GMSLRs of 0.5 to 2.0 m by 2100. Upgrading coastal defenses and nourishing beaches would reduce these impacts roughly by three orders of magnitude. Hinkel et al. (2013) estimate the number of people flooded annually in 2100 to reach 117 to 262 million per year in 2100 without upgrading protection and two orders of magnitude smaller with dike (levee) upgrades, given GMSLRs of 0.6 to 1.3 m by 2100. The major driver of increasing risks to human settlements in the next decades is socioeconomic development. When upgrading flood defenses to maintain a constant probability of flooding, average annual losses (AALs) in the 136 largest coastal cities are expected to increase ninefold from 2005 to 2050 due to socioeconomic development, only another 12% due to subsidence, and 2 to 8% due to GMSLRs of 0.2 to 0.4 m (Hallegate et al., 2013; Figure 5-4).

Despite the delayed response of sea level rise to global warming levels (WGI AR5 Section 13.5.4) mitigation may limit 21st century impacts of increased coastal flood damage, dry-land loss, and wetland loss substantially (*limited evidence*, *medium agreement*) albeit numbers are difficult to compare owing to differences in scenarios, baselines, and adaptation assumptions. Tol (2007) finds that stabilizing CO_2 concentration at 550 ppm reduces global impacts on wetlands and dry lands by about 10% in 2100 compared to a scenario of unmitigated emissions. Hinkel et al. (2013) report that stabilizing emissions at 450 ppm CO_2-eq reduces the average number of people flooded in 2100 by about 30% compared to a baseline where emissions increase to about 25 Gt C-eq in 2100. Arnell et al. (2013) find that an emissions pathway peaking in 2016 and declining at 5% per year thereafter reduces flood risk by 58 to 66% compared to an unmitigated A1B scenario. All three studies only consider the effects of mitigation during the 21st century and assume low or no contribution of ice sheets to GMSLR. Mitigation is expected to be more effective when considering impacts beyond 2100 and higher contributions of ice sheets (Section 5.5.8).

Global studies confirm AR4 findings that there are substantial regional differences in coastal vulnerability and expected impacts (*high confidence*). Most countries in South, Southeast, and East Asia are particularly vulnerable to sea level rise due to rapid economic growth and coastward migration of people into urban coastal areas together with high rates of anthropogenic subsidence in deltas where many of the densely populated areas are located (Nicholls and Cazenave, 2010). At the same time, economic growth in these countries increases the monetary capacity to adapt (Nicholls et al., 2010). In contrast, although many African countries experience a similar trend in rapid urban coastal growth, the level of economic development is generally lower and consequently the monetary capacity to adapt is smaller (Kebede and Nicholls, 2012; Hinkel et al., 2013).

In summary, while there is *high agreement* on some general findings, only a small fraction of the underlying uncertainty has been explored, which means evidence is limited. Gaps remain with respect to impacts of possible large contributions of the ice sheets of Greenland and Antarctica to GMSLR (WGI AR5 Sections 13.4.3, 13.4.4), regional patterns of climate-induced sea level rise, subsidence, and socioeconomic change and migration. Many studies rely on few or only a single socioeconomic scenario. Few studies consider adaptation and those that do generally ignore the wider range of adaptation measures beyond hard protection options. Integrated studies considering the interactions between a wide range of RSLR impacts (Table 5-3) as well as trade-offs between diverse adaptation options are missing.

5.4.3.2. Industry, Infrastructure, Transport, and Network Industries

Coastal industries, their supporting infrastructure including transport (ports, roads, rail, airports), power and water supply, storm water, and sewerage are highly sensitive to a range of extreme weather and climate events including temporary and permanent flooding arising from extreme precipitation, high winds, storm surges, and sea level rise (Horton et al. 2010; Handmer et al. 2012; Hanson and Nicholls, 2012; Aerts et al. 2013; *high confidence*). Most industrial facilities, infrastructure, and networks are designed for service lives extending over several decades. In fact, many bridges, ports, and road and railway lines remain in their original design location for centuries even if the infrastructure on them has been rehabilitated or replaced several times. Certain facilities, such as new nuclear power plants, are designed to last even well beyond the 22nd century (Wilby et al., 2011).

As the need to locate most of these industries and networks in coastal areas will remain and probably increase due to coastal development (Section 5.4.3.1), considering climate variability and climate change drivers in life cycle assessment of industry, infrastructure, and transport and network industries is of utmost importance (*high confidence*).

5.4.3.2.1. Observed impacts

Climate impacts on coastal industries and infrastructures vary considerably depending on geographical location, associated weather and climate, and specific composition of industries within particular coastal regions (*high confidence*).

Over the last 10 years an extensive number of climate-related extreme events (Coumou and Rahmstorf, 2012) illustrate the potential for impacts on coastal industry, infrastructure, transport, and network industry. Severe storms with associated winds, waves, rain, lightning, and storm surges have been particularly disruptive to transport and power and water supplies (Jacob et al., 2007; USCCSP, 2008; Horton et al., 2010; *high confidence*). In such network configurations, flooding of even the smallest component of an intermodal system can result in a much larger system disruption. Even though a transportation terminal may not be affected, the access roads to it could be, thus forcing the terminal to cease or reduce operation. Disruption to port activities in one location can disrupt supply chains, which can have far reaching consequences (Becker et al. 2012, 2013). Existing experience has also shown that impacts of hurricanes and flooding on underground infrastructure can have long-term effects (Chisolm and Matthews, 2012).

Hurricanes like Katrina (2005) caused US$100 million of damage to Mississippi's ports and Sandy (2012) led to a week-long shut-down of the Port of New York, generating economic damages reaching US$50 billion (Becker et al., 2012). These have shown the critical need to better prepare coastal human settlements and associated network infrastructures and industries for future extreme weather impacts and climate change (Aerts et al., 2013; *high confidence*).

5.4.3.2.2. Projected impacts

Although there is *robust evidence* of the impacts and consequences of extreme events on coastal infrastructure and industrial facilities, there are limited assessments on projected impacts of long-term changes (*high agreement*). Besides, while there is an important amount of non-journal literature on projected impacts of sea level rise and increasing flooding levels on certain coastal infrastructures (USCCSP, 2008; USACE, 2011; McEvoy and Mullet, 2013), limited peer review information is available.

Vulnerability to flooding of railroads, tunnels, ports, roads, and industrial facilities at low-lying areas will be exacerbated by rising sea levels or more frequent or intense storms, causing more frequent and more serious disruption of services and damages under extreme sea levels unless adaptation is enforced (Esteban et al., 2010, 2012; Wilby et al., 2011; Aerts et al., 2013; *high confidence*).

Furthermore, sea level rise will reduce extreme flood return periods and therefore increase the need for adaptation of infrastructure such as airports, tunnels, coastal protections, and ship terminals to extreme sea level impacts (Jacob et al., 2007; Becker et al., 2013).

It is estimated that a hypothetical 1 m RSLR projected for the Gulf Coast region between Alabama and Houston over the next 50 to 100 years would permanently flood a third of the region's roads as well as putting more than 70% of the region's ports at risk (USCCSP, 2008).

The estimated costs of climate change to Alaska's public infrastructure could add US$3.6 to 6.1 billion (+10 to 20% above normal wear and tear) from now to 2030 and US$5.6 to 7.6 billion (+10 to 12%) from now to 2080 (Larsen et al., 2008). Higher costs of climate change for coastal infrastructure are expected due to its proximity to the marine environment. Other projected impacts are beneficial for the transportation system. For example, decline of Arctic sea-ice coverage could extend seasonal accessibility to high-latitude shipping routes such as the northwest shipping route that connects the Atlantic to the North Pacific.

Hanson et al. (2011) presents a first estimate of the exposure of the world's large port cities to coastal flooding due to sea level rise and storm surge in the 2070s. The analysis suggests that the total value of assets exposed in 2005 across all cities considered is estimated to be US$3000 billion, corresponding to around 5% of global GDP in 2005. By the 2070s, and assuming a homogeneous global sea level rise of 0.5 m, increased extreme water levels up to 10%, and a fixed subsidence rate in susceptible cities with respect to today's values, asset exposure is estimated to increase to approximately 9% of projected global GDP in this period.

Coastal infrastructural instability may result from natural hazards triggered by groundwater-level (GWL) variations resulting from rising sea level. For earthquake-prone coasts, this could be exacerbated by earthquake liquefaction if GWL increases with sea level rise (Yasuhara et al., 2007). Increasing sea levels, surges, and waves can also lead to a stability loss of coastal structures (Headland et al., 2011).

Other impacts may arise in coastal industries in high latitudes affected by permafrost thaw causing ground instability and erosion, thereby affecting transport safety and the industries that rely on such travel in these regions (e.g., Pearce et al., 2010).

5.4.3.3. Fisheries, Aquaculture, and Agriculture

Fisheries and aquaculture and the associated post-harvest activities globally create millions of jobs (Daw et al., 2009; Sumaila et al., 2011) and contribute significantly to the dietary animal protein of millions of people and to the world merchandise trade (FAO, 2010, 2012; see also Section 6.4.1.1). In addition to small-scale fisheries and aquaculture, which are important for the food security and economy of coastal communities (Bell et al., 2009), coastal zones also support significant agricultural activities, for example, rice production in the low-lying deltaic regions of Asia (Wassmann et al., 2009).

5.4.3.3.1. Observed impacts

Climate variability and change impact both fishers' livelihoods (Badjeck et al., 2010) and fish production (Barange and Perry, 2009) (Section 6.5.3). In the North Sea, ocean warming over the 1977–2002 period led to relatively increased distribution ranges of some fish species (Hiddink and Hofstede, 2008), and demersal fish assemblage deepened in response to climate change (Dulvy et al., 2008). In southeastern Australia, Last et al. (2011) found an increasing abundance of 45 fish species of warm temperate origin, which they linked to the observed strengthening of the East Australian Current (EAC) bringing warm waters further south (Ridgeway, 2007). A study (Sherman et al., 2009) of the impact of sea surface temperature changes on the fisheries yields of 63 large marine ecosystems over a 25-year period shows a positive relationship for the northeast Atlantic large marine ecosystems, due to zooplankton biomass increases (Section 6.5.3). Distributional effects are very important for migratory pelagic fisheries, such as tuna (see Table 29-2). Impacts of climate change on aquaculture (*Mytilus edulis* and *Salmo salar*) in the UK and Ireland have been difficult to discern from natural environmental variability (Callaway et al., 2012).

Seawater inundation has become a major problem for traditional agriculture in Bangladesh (Rahman et al., 2009), and in low-lying island nations (e.g., Lata and Nunn, 2012). The combination of rice yield reduction induced by climate change and inundation of lands by seawater causes an important reduction in production (Chen et al., 2012).

5.4.3.3.2. Projected impacts

Fisheries may be impacted either negatively or positively (Hare et al., 2010; Meynecke and Lee, 2011; Cinner et al., 2012) depending on the latitude, location, and climatic factors. Climate change can impact the pattern of marine biodiversity through changes in species' distributions, and may lead to large-scale redistribution of global catch potential depending on regions (Cheung et al., 2009, 2010). Narita et al. (2012) estimated that the global economic costs of production loss of molluscs due to ocean acidification (Section 5.3.3.5) by the year 2100 based on IPCC IS92a business-as-usual scenario could be higher than US$100 billion. As a result of increased sea temperatures, the reduction in coral cover in the Caribbean basin and its associated fisheries production is expected to lead to a net revenue loss by 2015 (Trotman et al., 2009). Economic losses in landed catch value and the costs of adapting fisheries resulting from a 2°C global temperature increase by 2050 have been estimated at US$10 to 31 billion globally (Sumaila et al., 2011). For aquaculture, negative impacts of rising ocean temperatures will be felt in the temperate regions whereas positive impacts will be felt in the tropical and subtropical regions (De Silva and Soto, 2009). Changes to the atmosphere-ocean in the Pacific Island countries are likely to affect coral reef fisheries by a decrease of 20% by 2050 and coastal aquaculture may be less efficient (Bell et al., 2013).

In summary, changes have occurred to the distribution of fish species (*medium confidence*) with evidence of poleward expansion of temperate species (*limited evidence*, *high agreement*). Tropical and subtropical aquaculture has not been adversely affected by rising ocean temperatures to date (*limited evidence*, *high agreement*). Coastal agriculture has experienced negative impacts (*medium confidence*) due mainly to increased frequency of submersion of agricultural land by saltwater inundation (*limited evidence*, *high agreement*).

5.4.3.4. Coastal Tourism and Recreation

Coastal tourism is the largest component of the global tourism industry. Over 60% of Europeans opt for beach holidays and beach tourism provides more than 80% of U.S. tourism receipts (UNEP, 2009). More than 100 countries benefit from the recreational value provided by their coral reefs, which contributed US$11.5 billion to global tourism (Burke et al., 2011).

5.4.3.4.1. Observed impacts

Observed significant impacts on coastal tourism have occurred from direct impacts of extreme events on tourist infrastructure (e.g., beach resorts, roads), indirect impacts of extreme events (e.g., coastal erosion, coral bleaching), and short-term adverse tourist perception after the occurrence of extreme events (e.g., flooding, tropical storms, storm surges) (Phillips and Jones, 2006; Scott et al., 2008; IPCC, 2012, Section 4.3.5.3). Recent observed climate change impacts on the Great Barrier Reef include coral bleaching in the summers of 1997–1998, 2001–2002, and 2005–2006 and extreme events including floods and cyclones (Tropical cyclones Larry in 2006, Hamish in 2009, and Yasi in 2011). The stakeholders show a high level of concern for climate change, and various resilience initiatives have been proposed and developed by the Great Barrier Reef Marine Park Authority (Biggs, 2011; GBRMPA, 2012).

5.4.3.4.1. Projected impacts

To provide some idea of climate change impacts on coastal destinations, many studies have been carried out on projecting tourism demand, for

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example, in Europe (Perch-Nielson et al., 2010), in the Baltic region (Haller et al., 2011), in the Mediterranean (Moreno and Amelung, 2009a), and in 51 countries worldwide (Perch-Nielson, 2010). The studies provide varying details, although it is difficult to draw overarching conclusions on tourism demand for coastal destinations. With increased temperature in mid-latitude countries and coupled with increased storms in tropical areas, tourist flows could decrease from mid-latitude countries to tropical coastal regions with large developing countries and small island nations most affected (Perch-Nielson, 2010). The Mediterranean would likewise be affected in summer (Moreno and Amelung, 2009a). In contrast, less is known about the relationship between the impacts of climate change and specific tourist behavior, activities, or flows to coastal destinations (Moreno and Amelung, 2009b; see Section10.6.2). Usually tourists do not consider climate variability or climate change in their holidays (Hares et al., 2009) although there are a few studies that show the contrary (Cambers, 2009; Alvarez-Diaz et al., 2010).

As for future impacts on coastal tourism, there is *high confidence* in the impacts of extreme events and sea level rise aggravating coastal erosion. A scenario of 1-m sea level rise by 2100 would be a potential risk to Caribbean tourism (Scott et al., 2012). The presence of coastal tourism infrastructure will continue to exacerbate beach reduction and coastal ecosystems squeeze under rising sea levels, as exemplified in Martinique (Schleupner, 2008). Carbonate reef structures would degrade under a scenario of at least 2°C by 2050–2100 with serious consequences for tourism destinations in Australia, the Caribbean, and other small islands (Hoegh-Gulberg et al., 2007; see Box CC-CR).

The costs of future climate change impacts on coastal tourism are enormous. For example, in the Caribbean community countries, rebuilding costs of tourist resorts are estimated US$10 to 23.3 billion in 2050. A hypothetical 1-m sea level rise would result in the loss or damage of 21 airports, inundation of land surrounding 35 ports, and at least 149 multi-million dollar tourism resorts damaged or lost from erosion to the coastal beach areas (Simpson et al., 2010).

In summary, while coastal tourism can be related to climate change impacts, it is more difficult to relate tourism demand directly to climate change. Coastal tourism continues to be highly vulnerable to weather, climate extremes, and rising sea levels with the additional sensitivity to ocean temperature and acidity for the sectors that rely on reef tourism (*high confidence*). Developing countries and small island states within the tropics relying on coastal tourism are most vulnerable to present and future weather and climate extremes, future sea level rise, and the added impacts of coral bleaching and ocean acidification (*high confidence*).

5.4.3.5. Health

The relationship between health of coastal populations and climate change include direct linkages (e.g., floods, droughts, storm surges, and extreme temperatures) and indirect linkages (e.g., changes in the transmission of vector-, food-, and water-borne infectious diseases and increased salinization of coastal land that affects food production and freshwater supply and ecosystem health). Coastal and particularly informal settlements concentrate injury risk and death from storm surges and rainfall flooding (Handmer et al., 2012). This section deals with human health in the context of the coastal zone, while Chapter 11 addresses general health issues and Section 6.4.2.3 deals with health issues associated with ocean changes. Understanding the relationship between climate and health is often confounded by socioeconomic factors that influence coastal settlement patterns and the capacity of authorities to respond to health-related issues (Baulcomb, 2011).

5.4.3.5.1. Observed impacts

Mortality risk in coastal areas is related to exposure and vulnerability of coastal populations to climate hazards (e.g., Myung and Jang, 2011). A regional analysis of changes in exposure, vulnerability, and risk indicates that although exposure to flood and cyclone hazards has increased since 1980, the risk of mortality has generally fallen. The reductions reflect a strengthening of the countries' capacity to respond to disasters (Box 5-1). However, mortality is still rising in the countries with the weakest risk governance capacities (UNISDR, 2011).

Coastal regions face a range of climate-sensitive diseases. Increased saline intrusion is linked to increased hypertension disease (Vineis et al., 2011), with greater occurrence in pregnant women living in coastal regions compared to further inland (Khan et al., 2008). Increasing temperature, humidity, and rainfall can increase vector-borne diseases such as malaria, dengue, leishmaniasis, and chikungunya (Pialoux et al., 2007; Stratten et al., 2008; Kolivras, 2010; van Kleef et al., 2010) and diarrhea, infectious gastrointestinal disease, rotovirus, and salmonella (e.g., Hashizume et al., 2007; Zhang et al., 2007, 2010; Chou et al., 2010; Onozuka et al., 2010). The parasitic disease schistosomiasis, endemic in many tropical and small island coastal regions (Section 29.3.3.2), is also sensitive to temperature increase (Mangal et al., 2008). Vibrio outbreaks (e.g., cholera) are sensitive to rainfall and SST (e.g., Koelle et al., 2005), and recent increased vibrio outbreaks in the Baltic have been linked to heat waves and low salinity (Baker-Austin et al., 2013). Harmful algal blooms (HABs) outbreaks (e.g., ciguatera) have been linked to SST variability (e.g., Erdner et al., 2008; Jaykus et al., 2008). However, in general there is *limited evidence* and *low confidence* in how global climate change will impact HABs (Section 6.4.2.3), suggesting the need for increased monitoring (Hallegraeff, 2010). Nontoxic blooms of high biomass can reduce biodiversity through oxygen depletion and shading (Erdner et al., 2008), with consequences for ecosystem and human nutrition and health.

5.4.3.5.2. Projected impacts

Under future climate conditions, expansion of brackish and saline water bodies in coastal areas under projected sea level rise may increase the incidence of vector-borne diseases (Ramasamy and Surendran, 2011), diarrhea, and hypertension (Vineis et al., 2011). Human responses to climate change may also influence outcomes on health; however, limited empirical climate-health data increases uncertainties on such projections (Kolstad and Johansson, 2011).

Evidence continues to emerge of the relation between climate and diseases that affect human health in the coastal zone including air and water temperature, rainfall, humidity, and coastal salinity. However, the relations are often complex and vary between diseases and even regionally for the same disease. The interplay between climate and human systems with regard to health impacts is poorly understood and this continues to confound reliable projections of health impacts (*robust evidence*, *high agreement*).

5.4.4. Summary: Detection and Attribution

There is *high confidence* in the attribution to climate change of observed coastal impacts that are sensitive to ocean temperature change, such as coral bleaching and movements in species ranges. However, for many other coastal changes, the impacts of climate change are difficult to tease apart from human-related drivers (e.g., land use change, coastal development, pollution). Figure 5-5 shows changes of major phenomena observed in coastal systems and low-lying areas. Horizontal and vertical axes indicate the degree of confidence in detection of trends for phenomena, which are elements sensitive to climate change, and the degree of confidence in attribution of phenomena to climate change, respectively. Mainly phenomena with *high* to *very high confidence* in trend detection are illustrated in this figure.

The increase of coral bleaching and the shift in distribution and range limits of some species are attributed to climate change with *high confidence.* Mass coral bleaching coincided with positive temperature anomalies over the past 30 years. A poleward expansion of mangrove forests and some corals, and shifts of range limits of many intertidal species, are also attributed. Vegetated coastal habitats are declining globally. Coral cover and calcification have decreased in recent decades. Elevated temperatures along with ocean acidification reduce the calcification rate of corals. Although the attribution of decreased calcification to either climate- or human-related drivers is difficult, we have *medium confidence* that the primary climate-related driver is ocean warming globally. Seagrass meadows are already under stress due to climate change, particularly where maximum temperatures already approach their physiological limit. However, the decline of the distribution of mangroves and salt marshes is mainly linked with human activities, for example, deforestation and reclamation. Therefore the degree of their attribution to climate change is *very low*.

Globally beaches and shorelines have, in general, undergone net erosion over the past century or longer. There is *high confidence* in detection of increased beach erosion globally. However, attributing shoreline changes to climate change is still difficult owing to the multiple natural and human-related drivers contributing to coastal erosion (e.g., subsidence, decreased sediment delivery, land use change). There is *high confidence* that human pressures, for example, increased usage of surface water and groundwater resources for agriculture and coastal settlements, and river channel deepening, have led to increased saltwater intrusion and *low confidence* in attribution of saltwater intrusion to climate change.

The population living in coastal lowlands is increasing and more than 270 million people in 2010 are already exposed to flooding by the 1-in-100-year coastal flood (Mimura, 2013). Population growth and land subsidence in coastal lowlands are the major causes; therefore, there is *very low* attribution to climate change.

5.5. Adaptation and Managing Risks

5.5.1. Introduction

Coastal adaptation and risk management refer to a wide range of human activities related to the social and institutional processes of framing the

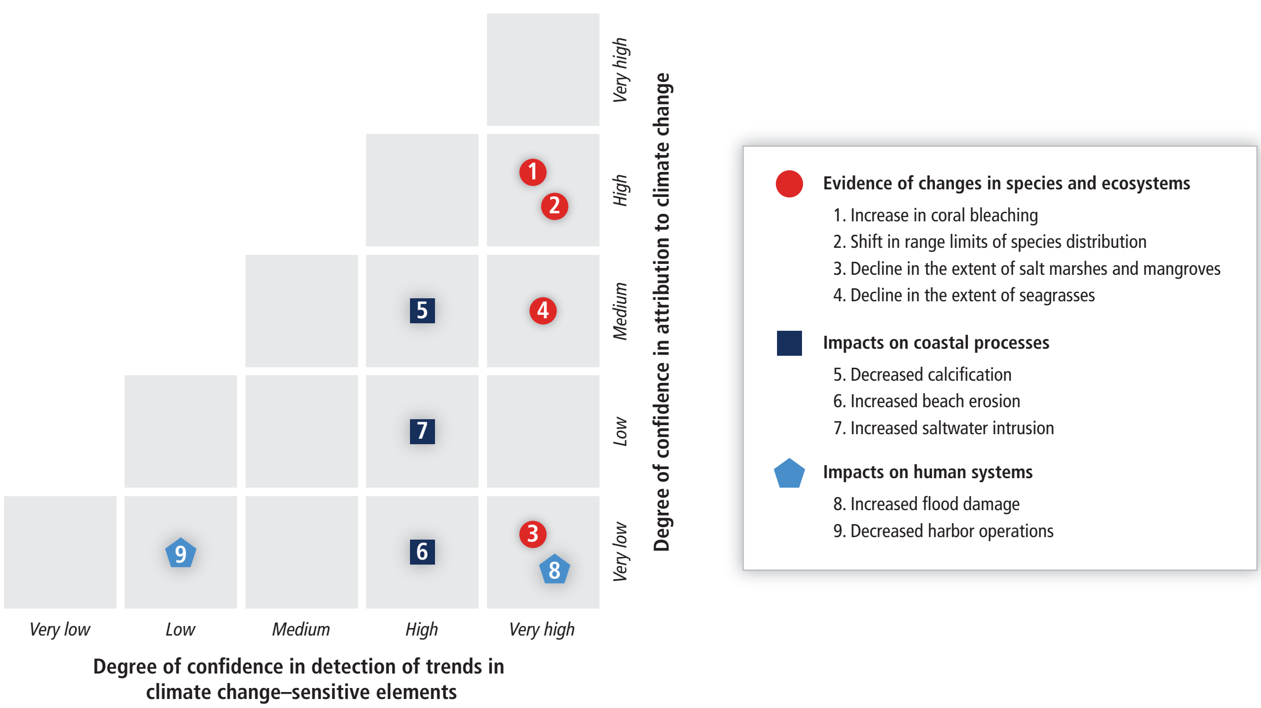

Figure 5-5 | Summary of detection and attribution in coastal areas.

Frequently Asked Questions

FAQ 5.3 | How can coastal communities plan for and adapt to the impacts of climate change, in particular sea level rise?

Planning by coastal communities that considers the impacts of climate change reduces the risk of harm from those impacts. In particular, proactive planning reduces the need for reactive response to the damage caused by extreme events. Handling things after the fact can be more expensive and less effective.

An increasing focus of coastal use planning is on precautionary measures, that is, measures taken even if the cause and effect of climate change is not established scientifically. These measures can include things like enhancing coastal vegetation and protecting coral reefs. For many regions, an important focus of coastal use planning is to use the coast as a natural system to buffer coastal communities from inundation, working with nature rather than against it, as in the Netherlands.

While the details and implementation of such planning take place at local and regional levels, coastal land management is normally supported by legislation at the national level. For many developing countries, planning at the grass roots level does not exist or is not yet feasible.

The approaches available to help coastal communities adapt to the impacts of climate change fall into three general categories:

1. Protection of people, property, and infrastructure is a typical first response. This includes "hard" measures such as building seawalls and other barriers, along with various measures to protect critical infrastructure. "Soft" protection measures are increasingly favored. These include enhancing coastal vegetation and other coastal management programs to reduce erosion and enhance the coast as a barrier to storm surges.
2. Accommodation is a more adaptive approach involving changes to human activities and infrastructure. These include retrofitting buildings to make them more resistant to the consequences of sea level rise, raising low-lying bridges, or increasing physical shelter capacity to handle needs caused by severe weather. Soft accommodation measures include adjustments to land use planning and insurance programs.
3. Managed retreat involves moving away from the coast and may be the only viable option when nothing else is possible.

Some combination of these three approaches may be appropriate, depending on the physical realities and societal values of a particular coastal community. The choices need to be reviewed and adjusted as circumstances change over time.

adaptation problem, identifying and appraising adaptation options, implementing options, and monitoring and evaluating outcomes (Chapters 2, 14, 15, 16, and 17). The governance of this process is challenging due to the complex, nonlinear dynamics of the coastal socio-ecological systems (Rosenzweig et al., 2011) as well as the presence of multiple management goals, competing preferences of stakeholders, and social conflicts involved (Hopkins et al., 2012). In many instances, coastal adaptation may thus be characterized to be a "wicked problem" (Rittel and Webber, 1973), in the sense that there is often no clear agreement about what exactly the adaptation problem is and there is uncertainty and ambiguity as to how improvements might be made (Moser et al., 2012).

Since AR4, the set of adaptation measures considered has been expanded specifically toward ecosystem-based measures (Section 5.5.2); novel approaches for appraising coastal adaptation decisions have been applied (Section 5.5.3.1) and the analysis of adaptation governance and the institutional context in which decisions are taken has progressed (Section 5.5.3.2). Progress has also been made in better integrating adaptation practices within existing policy frameworks (Section 5.5.4.1) as well as in implementing adaptation and identifying good practices (Section 5.5.4.2). A number of studies have also explored the global costs and benefits of coastal adaptation (Section 5.5.5); opportunities, constraints, and limits of coastal adaptation (Section 5.5.6); linkages between coastal adaptation and mitigation (Section 5.5.7); and the long-term commitment to coastal adaptation (Section 5.5.8).

5.5.2. Adaptation Measures

A detailed discussion on general adaptation needs and measures can be found in Chapter 14. As a first approximation, adaptation measures were classified into institutional and social measures (Section 14.3.2.1), technological and engineered measures (Section 14.3.2.2), and ecosystem-based adaptation measures (Section 14.3.2.3). In terms of coastal adaptation, most of the existing measures can be included within this classification.

The IPCC classification of coastal adaptation strategies consisting of retreat, accommodation, and protection (Nicholls et al., 2007) is now widely used and applied in both developed and developing countries (Boateng, 2010; Linham and Nicholls, 2012). This trilogy of strategies has expanded into broad approaches of retreat, defend, and attack (Peel, 2010). Protection aims at advancing or holding existing defense lines by means of different options such as land claim; beach and dune nourishment; the construction of artificial dunes and hard structures such as seawalls, sea dikes, and storm surge barriers; or removing invasive and restoring native species. Accommodation is achieved by increasing flexibility, flood proofing, flood-resistant agriculture, flood hazard mapping, the implementation of flood warning systems, or replacing armored with living shorelines. Retreat options include allowing wetlands to migrate inland, shoreline setbacks, and managed realignment by, for example, breaching coastal defenses allowing the creation of an intertidal habitat. The appropriate measure may depend on several factors requiring a careful decision-making and governance process (Section 5.5.3).

Since AR4, coastal adaptation options have been revised and summarized in several guidebooks (EPA, 2009; USAID, 2009; UNEP, 2010) including best practice examples. Especially relevant has been the growth of Community Based Adaptation (CBA) measures (*robust evidence*, *high agreement*). Table 5-4 compiles different examples of CBA measures in countries such as Bangladesh, India, and the Philippines.

Ecosystem-based adaptation is increasingly attracting attention (Munroe et al., 2011). Adaptation measures based on the protection and restoration of relevant coastal natural systems such as mangroves (Schmitt et al., 2013), oyster reefs (Beck et al., 2011), and salt marshes (Barbier et al., 2011) are seen as no- or low-regret options irrespective of future climate (Cheong et al., 2013; *medium evidence*, *high agreement*). Further work is still needed in order to make reliable quantitative estimates and predictions of the capability of some of these ecosystems to reduce wave, storm surge, and sea level rise impacts and in order to provide reliable cost-benefit analysis of how they compare to other measures based on traditional engineering approaches.

5.5.3. Adaptation Decision Making and Governance

Since AR4, progress has been made in understanding coastal adaptation decisions and governance. For a general treatment of adaptation decision making and governance, see Chapters 2, 15, and 17.

5.5.3.1. Decision Analysis

One specific quality of many coastal adaptation decisions is that these involve options with long (i.e., 30 and more years) investment time scales (e.g., land use planning, flood defenses, construction of housing, and transportation infrastructure; Section 5.5.2). For such decisions, standard methods that rely on probability distribution of outcomes, such as cost-benefit analysis under uncertainty, cannot be applied because of the difficulties, both in theory and practice, to associate probabilities to future levels of GHG emissions, which determine the level of impacts and outcomes (Lempert and Schlesinger, 2001; Hallegate, 2009; see also Section 17.3.6.2).

Alternative approaches that represent uncertainty not through a single probability distribution but through a range of scenarios have thus been applied to long-term coastal adaptation. Robust decision making (RDM), for example, refers to approaches where options that work well over a wide range of these scenarios are preferred (Lempert and Schlesinger, 2000; Lempert and Collins, 2007). RDM in this sense has been applied to, e.g., the Port of Los Angeles infrastructure (Lempert et al., 2012).

Another set of approaches uses the criterion of flexibility to decide between alternative strategies. Flexible and reversible options are favored over non-flexible and non-reversible ones and decisions are delayed to keep future options open (Hallegate, 2009). The adaptation pathways approach, for example, implements the criterion of flexibility by characterizing alternative strategies in terms of two attributes: (1) adaptation tipping points (ATPs), which are points beyond which strategies are no longer effective (Kwadijk et al., 2010); and (2) what alternative strategies are available once a tipping point has been reached (Haasnoot et al., 2013). Importantly, the exact time when an ATP is reached does not matter; it is rather the flexibility of having alternative strategies available that is driving the decision. Prominent applications of this approach include the Thames Estuary 2100 Plan (Penning-Roswell et al., 2012; Box 5-1), the Dutch Delta Programme (Kabat et al., 2009), and the New York City Panel on Climate Change (Rosenzweig et al., 2011).

5.5.3.2. Institution and Governance Analysis

Decisions are made within a context. Institution and governance analysis comprise a variety of approaches that aim at describing this context as well as at explaining the emergence and performance of institutions and governance structures (GS). Institution analysis is particularly relevant to coastal adaptation, because deciding between options and implementing them is an ongoing process involving complex inter-linkages between public and private decisions at multiple levels of decision making and in the context of other issues, existing policies, conflicting interests, and diverse GS (e.g, Few et al., 2007; Urwin and Jordan, 2008; Hinkel et al., 2010; see also Sections 2.2.2, 2.2.3). The non-consideration of this context may hinder or mislead adaptation decisions and implementations as reported by the emerging literature on barriers to adaptation (Section 5.5.5). Institution analysis strives to understand how this context shapes decisions, and insights gained may be employed to craft effective institutions and policies for adaptation.

For coastal adaptation, the effectiveness of existing GS is often hindered owing to a lack of horizontal (i.e., within the same level of decision making) and vertical (i.e., between different levels of decision making) integration of organizations and policies (*high confidence*). Storbjörk and Hedren (2011), for example, report on a weak vertical administrative interplay in coastal GS in Sweden. In the UK, the effectiveness of local GS of Coastal Partnership is found to be limited because these are poorly integrated with higher level policies (Stojanovic and Barker, 2008). In the UK, national level coastal recommendations are difficult to translate into local level actions (Few et al., 2007) and, in the USA, coastal policies often have ambiguous or contradictory goals (Bagstad et al., 2007). In a number of African cases, coastal policies are found not to take into account longer term climate change (Bunce et al., 2010).

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Box 5-1 | London's Thames Estuary 2100 Plan: Adaptive Management for the Long Term

The Environment Agency in Britain has recently developed the Thames Estuary 2100 plan (TE2100) to manage future flood threat to London (Environment Agency, 2012). The motivation was a fear that due to accelerated climate change-induced sea level rise the time could already be too short for replacing the Thames Barrier (completed in 1982) and other measures that protect London, because such major engineering schemes take 25 to 30 years to plan and implement. An adaptive plan that manages risk in an iterative way was adopted based on the adaptation pathway approach (Penning-Rowsell et al., 2012; see also Section 5.5.3.1; Figure 5-6). This plan includes maintaining the existing system in the first 25 years, then enhancing the existing defenses in a carefully planned way over the next 25 to 60 years, including selectively raising defenses and possibly over-rotating the Barrier to raise protection standards. Finally, in the longer term (beyond 2070) there will be the need to plan for more substantial measures if sea level rise accelerates. This might include a new barrier, with even higher protection standards, probably nearer to the sea, or even a coastal barrage. In the meantime the adaptive approach requires careful monitoring of the drivers of risk in the Estuary to ensure that flood management authorities are not taken by surprise and forced into emergency measures.

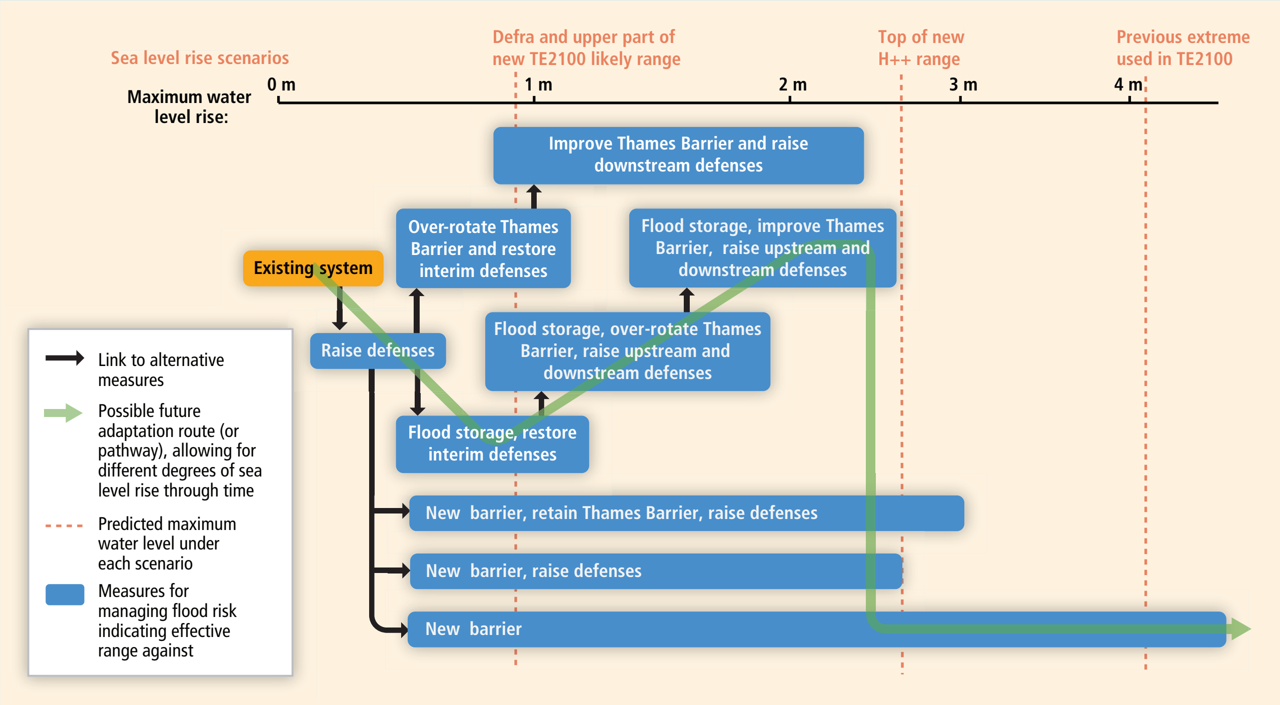

Figure 5-6 | Adaptation measures and pathways considered in the TE2100 project. The boxes show the measures and the range of sea level rise over which the measures are effective. The black arrows link to alternative measures that may be applied once a measure is no longer effective. The red lines show various 21st century sea level rise scenarios used in the analysis including a conservative estimate of about 0.9 m by the UK Department for Environment Food and Rural Affairs ('Defra and upper part of new TE2100 likely range'), a high-level scenario ('Top of new H++ range'), and an extreme scenario of over 4 meters ('previous extreme used in TE2100'). The fat green line shows a possible future adaptation route (or pathway), allowing for different degrees of sea level rise through time (adapted from Lowe et al., 2009).

Governance issues are particularly challenging when considering planned retreat (*medium evidence*). While managed realignment is on the political agenda in Germany and the UK, the political costs of doing so are high, as both the existing GS as well as public opinion are geared toward protection (e.g., Tunstall and Tapsell, 2007), so that short election cycles do not provide incentives for politicians to undertake actions that may produce benefits in the long term (Few et al., 2007; Rupp-Armstrong and Nicholls, 2007). Along the Queensland coast in Australia the option of planned retreat is disappearing because of rapid coastal development and liability laws favoring development. To prevent this, risks and responsibilities would need to be redistributed from the governments to the beneficiaries of this development (Abel et al., 2011).

While institutional factors are decisive in enabling coastal adaptation (*high confidence*), the role of institutions in coastal adaptation is generally under-researched. The majority of studies are descriptive. Institutional analysis striving to understand which GS emerge and are effective depending on both biophysical and social system characteristics as found in the fields of socio-ecological systems (Dietz et al., 2003; Folke et al., 2005; Ostrom 2007, 2009) and institutional economics (Hagedorn et al., 2002; Bougherara et al., 2009) are practically nonexistent.

5.5.4. Implementation and Practice

Since AR4, more experience has been gained in coastal adaptation implementation and practice. Generally, adaptation is not carried out stand-alone but in the context of already existing policy and practice frameworks. Section 5.5.4.1 assesses frameworks that are particularly relevant for coastal adaptation, and Section 5.5.4.2 assesses the experience as well as principles and compiled best practice guidelines.

5.5.4.1. Frameworks

The issues for coastal adaptation are not radically different from issues encountered within ICZM, which offers an enabling environment for adaptation practice (Celliers et al., 2013). ICZM is a long-term, institutionalized and iterative process that promotes the integration of coastal activities, relevant policymakers, practitioners, and scientists across coastal sectors, space and organizations with a view to use coastal resources in a sustainable way (Christie et al., 2005; Kay and Alder, 2005; Sales, 2009; WGII AR5 Glossary). Considering climate change in this framework does not mean radical changes to ICZM, because ICZM already emphasizes the integration of coastal issues across sectors and policy domains as well as the long-term perspective (e.g., Hofstede, 2008; Falaleeva et al., 2011). The major difference of coastal adaptation from ICZM is coping with greater uncertainty, longer time frames in planning (beyond 30 years), and long-term commitments inherent to climate change (Tobey et al. 2010). So far, however, there is *limited evidence* and *low agreement* on the effectiveness of ICZM alone or combined with climate change adaptation. Even though ICZM has been applied throughout the world for over 40 years, many obstacles to its successful implementation still remain (*high confidence*). Generally, there is a lack of empirical research evaluating ICZM (Stojanovic et al., 2004; Stojanovic and Ballinger, 2009). A recent review of ICZM in Europe concluded that the complexity of coastal regulations, demographic deficits, lack of sustainable finance and a failure to involve communities, business, and industry hinder its implementation (Shipman and Stojanovic, 2007). Developing countries in particular struggle to meet the goals of ICZM owing to a lack of qualified human resources, a lack of human, legal, and institutional capacities (Isager, 2008; González-Riancho et al., 2009), difficulties in integrating policy across multiple coastal agencies (Martinez et al., 2011; Ibrahim and Shaw, 2012), power (abuse) of the majority political party or political leaders (Isager, 2008; Tabet and Fanning, 2012), the lack of long-term financial commitment of donors (González-Riancho et al., 2009; Ibrahim and Shaw, 2012), and a lack of knowledge regarding the coastal system (González-Riancho et al., 2009).

Another prominent framework used for coastal adaptation practice is adaptive management (AM), which has been developed as a response to the deep uncertainty characterizing ecosystem management, where it is often impossible to predict outcomes of management interventions. AM thus aims to test management hypothesis by implementing them, monitoring their outcomes and learning from these to refine the management hypothesis to be applied (Holling, 1978; Walters, 1986). There are numerous applications of AM to coastal management (e.g., Walters, 1997; Marchand et al., 2011; Mulder et al., 2011), but there is *limited evidence* of its long-term effectiveness. Limitations of AM are also notable, such as the potential high cost of experimentation and a range of institutional barriers hindering the delivery of flexible management approaches (e.g., McLain and Lee, 1996).

Community-based adaptation (CBA) refers to the generation and implementation of locally driven adaptation strategies that address both climate change impacts and development deficits for the climate-vulnerable poor and that aim to strengthen the adaptive capacity of local people to climate and non-climate risk factors (Nicholls et al., 2007; Reid et al., 2009; Ayers and Dodman, 2010; Ayers and Huq, 2013; see also Sections 14.2.1, 15.4.3.1, 24.4.6.5). CBA is a bottom-up approach to adaptation involving all relevant stakeholders, especially local communities (Ayers and Huq, 2009; UNDP, 2010; Riadh et al., 2012) (Table 5-4). As such, CBA approaches have been developed through active participatory processes with local stakeholders (Ayers and Forsyth, 2009), and operated on a learning-by-doing, bottom-up, empowerment paradigm (Kates, 2000; Huq and Reid, 2007).

CBA experiences emphasize that it is important to understand a community's unique perception of its adaptive capacities in order to identify useful solutions (Parvin et al., 2008; Badjeck et al., 2010; Paul and Routray, 2010) and that scientific and technical information on anticipated coastal climate impacts needs to be translated into a suitable language and format that allows people to be able to participate in adaptation planning (Saroar and Routray, 2010). Furthermore, effective CBA needs to consider measures that cut across sectors and technological, social, and institutional processes, as technology by itself is only one component of successful adaptation (Pelling, 2011; Rawlani and Sovacool, 2011; Sovacool et al., 2011).

Efforts are also being made to integrate climate change adaptation into Disaster Risk Reduction (DRR) frameworks (Mercer, 2010; Polack, 2010; Romieu et al., 2010; Gero et al., 2011) and adaptation practice is likely to move forward as climate change adaptation (CCA) converges with disaster risk reduction (UNISDR, 2009; Setiadi et al., 2010; Tran and Nitivattananon, 2011; Hay, 2012). In Japan, for example, coastal climate change adaptation has been mainstreamed into the framework of Coastal Disaster Management in the aftermath of the 2011 Tohoku Earthquake Tsunami. The priority of upgrading coastal defenses in the face of sea level rise is thereby judged from the potential damage on the assets in predicted inundation areas on the one hand as well as from the age and earthquake resistance of the coastal structures on the other hand (Central Disaster Management Council, 2011; Committee on Adaptation Strategy for Global Warming in the Coastal Zone, 2011). Other important policy and practice frameworks in place in the coastal zone include poverty reduction and development (Mitchell et al., 2010).

5.5.4.2. Principles, Guidance, and Experiences

Much of the observed adaptation practice deals with the coastal hazards of erosion and flooding (Hanak and Moreno, 2012). In many

Table 5-4 | Community-based adaptation measures.

Impact	Type of option	Measures	Brief description	References
Increased salinity	New and diversified livelihoods	Saline-tolerant crop cultivation	Farmer production of saline-tolerant multi-vegetable varieties and non-rice crops	Ahmed (2010); Rabbani et al. (2013)
	New and diversified livelihoods	Keora nursery	Mangrove fruit production to develop local female entrepreneurship	Ahmed (2010)
	New and diversified livelihoods	Crab fattening	Collection, rearing, and feeding of crabs for 15 days to increase local market value	Pouliotte et al. (2009)
	Structural	Homestead protection	Houses constructed on raised foundations to mitigate salinity ingress	Ayers and Forsyth (2009)
Flooding/ inundation	Socio-technical	Disaster management committees	Multi-community stakeholder committees established to discuss disaster preparedness and response on a monthly basis	Ahammad (2011)
	Socio-technical	Early flood warning systems	Established systems converted into a language and format understood by local communities; warning dissemination through community radio services	Ahmed (2005); Saroar and Routray (2010)
	New and diversified livelihoods	Aquaculture: cage and integrated approaches	Small-scale fish culture in cages on submerged agriculture land; aquaculture integrated with other livelihood practices	Pomeroy et al. (2006); Pouliotte et al. (2009); Khan et al. (2012)
	New and diversified livelihoods	Embankment cropping	Growing different vegetable varieties around heightened shrimp enclosures/coastal polders for productive use of fallow land	Ahmed (2010)
	New and diversified livelihoods	Hydroponics	Cultivating vegetables and other crops on floating gardens	Ayers and Forsyth (2009); Ahmed (2010); Dev (2013)
Cyclones/ storm surges	Structural/hard	Homestead reinforcement	Low-cost retrofitting to strengthen existing household structures, especially roofs; strict implementation of building codes	Sales (2009); Ahmed (2010)
	Structural/soft	Homestead ecosystem protection	Plantation of specific fruit trees around homestead area	Haq et al. (2012)
	Structural/hard	Underground bunker construction	Underground bunker established, providing protected storage space for valuable community assets	Raihan et al. (2010)
Sea level rise	Institutional	Risk insurance mechanisms	Farmers educated on comprehensive risk insurance, focusing on sea level rise and coastal agriculture	Khan et al. (2012)
Multi-coastal impacts	Institutional	Integrating climate change into education	Formal and informal teacher training and curriculum development on climate change, vulnerability, and risk management	Ahmed (2010)
	Institutional	Integrated coastal zone management (ICZM) plan	ICZM plan development at local institutional level, including land and sea use zoning for ecosystem conservation	Sales (2009)
	Structural/soft	Restoration, regeneration and management of coastal habitats	Community-led reforestation and afforestation of mangrove plantations, including integration of aquaculture and farming to increase household income levels	Rawlani and Sovacool, (2011); Sovacool et al. (2012)
	Institutional	Community participation in local government decision-making	Active female participation in local government planning and budgeting processes to facilitate delivery of priority coastal adaptation needs	Faulkner and Ali (2012)
	Institutional/ socio-technical	Improved research and knowledge management	Establishment of research centers; community-based monitoring of changes in coastal areas	Sales (2009); Rawlani and Sovacool (2011)

parts of the world, small island indigenous communities address climate change consequences based on their own traditional knowledge (Percival, 2008; Langton et al., 2012; Nakashima et al., 2012). Long-term adaptation to sea level rise has been confined to a few major projects such as the Venice Lagoon project, the Thames Estuary 2100 project (Box 5-1), and the Delta Programme, Netherlands (Norman, 2009).

Through the Delta Programme, the Dutch government has set out far-reaching recommendations on how to keep the country flood-proof over the 21st century taking into account a sea level rise as high as 0.65 to 1.3 m by 2100. These recommendations constitute a paradigm shift from "fighting" the forces of nature with engineered structures to "working with nature" and providing "room for river" instead (Kabat et al., 2009). The recommendations include soft and environmentally friendly solutions such as preserving land from development to accommodate increased river inundation, maintaining coastal protection by beach nourishment, improving the standards of flood protection, and putting in place the necessary political-administrative, legal, and financial resources (Stive et al., 2011).

From adaptation experiences, good practices (practices that have shown consistently better results and could be used as benchmark) have been derived. For some European cases, for example, McInnes (2006) has collected good practices for coastlines facing coastal erosion, flooding, and landslide events. In the California adaptation study that includes coasts, the lessons learnt include using best available science, decision on goals and early actions, locating relevant partners, identification and elimination of regulatory barriers, and encouragement of introduction of new state mandates and guidelines (Bedsworth and Hanak, 2010). Boateng (2010) presented 15 case studies from 12 countries of best practice in coastal adaptation to help coastal managers and policymakers. Bangladesh provides good examples on awareness raising, disaster warning and control, and protective building measures (Martinez et al., 2011). In general, documentation on good adaptation practices for coasts is improving.

In addition, numerous principles have been set forward. In a broad-scale assessment of climate change threats to Australia's coastal ecosystems, seven principles in adaptation were suggested: clearly defined goals by location, thorough understanding of connectivity within and between ecosystems, consideration of non-climatic drivers, involvement of all relevant stakeholders, easily available and shared data, re-thinking of existing policy and planning constraints, and adaptation at local/regional scales (Hadwen et al., 2011). Based on Oxfam's adaptation programs in South Asia that include coastal communities, additional principles presented include a focus on the poor, vulnerable, and marginalized; community or local ownership; flexible and responsive implementation; and preparation for future and capacity building at multiple levels (Sterrett, 2011). An assessment of worldwide case studies indicates the importance of knowledge transfer of good practice methods for scaling up adaptation strategies in and between regions and beyond the national scale (Martinez et al., 2011).

Further principles reported include: Information on efficient adaptation options alone (as assessed through DA approaches) may not fully serve the needs of managers and must to be supplemented by financial and technical assistance as well as boundary organizations that serve as an interface between science and practice (Tribbia and Moser, 2008). The adaptation and decision-making processes should be participatory and inclusive, integrating all relevant stakeholders in a way that is culturally appropriate (Milligan et al., 2009; Nunn, 2009). The adaptation processes should foster mutual learning, experimentation, and deliberation among stakeholders and researchers (Fazey et al., 2010; Kenter et al., 2011). For example, neither scientific climate knowledge alone nor indigenous knowledge alone is considered sufficient for coastal adaptation (Sales, 2009; Dodman and Mitlin, 2011; Bormann et al., 2012). Finally, since coastal systems are complex, diverse, and dynamic, their governance requires experimentation and learning by doing (Jentoft, 2007).

In summary, a wealth of adaptation activities can now be observed in the coastal zone that depend on technology, policy, financial, and institutional support, and are supported by documentation on good practices (*very high confidence*). ICZM, with its emphasis on integration, is likely to remain a major framework for coastal adaptation. While there is *high agreement* on adaptation principles, there is to date little systematic review of and hence *limited evidence* on why a given principle or approach is effective in a given context (and not in another), which emphasizes the need for research to better understand this context (Section 5.5.3.2). Some of the literature on adaptation practice needs to be treated with caution, because normative principles that have been established *ex ante* are not systematically distinguished from *ex post* evaluations of the experiences carried out. Despite the wealth of coastal adaptation activities, it must, however, be emphasized that meeting the multiple goals of coastal adaptation, improving governance, accounting for the most vulnerable populations and sectors and fully integrating consideration of natural ecosystems is still largely aspirational. Meanwhile, development continues in high-risk coastal areas, coastal ecosystems continue to degrade in many regions, coastal freshwater resources are being overexploited in many highly populated areas, and vulnerability to coastal disasters grows (e.g., Shipman and Stojanovic, 2007; McFadden, 2008; Jentoft, 2009; Mercer, 2010).

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5.5.5. Global Adaptation Costs and Benefits

This section reports on studies that provide internally consistent estimates of the direct costs of sea level rise impacts and adaptation at global scales. These studies have used the models FUND and DIVA, which are described in Section 5.4.1. Studies that use computable general equilibrium models and growth models to estimate the indirect and dynamic costs of climate change, including sea level rise, are reviewed in Chapter 10.

Generally, cost estimates are difficult to compare across studies owing to differences in scenarios used, impacts and adaptation options considered, methodologies applied, and baseline conditions assumed. Global adaptation costs have only been assessed for protection via dikes and nourishment. Nicholls et al. (2011) estimate annual adaptation cost in terms of dike construction, dike maintenance, and nourishment to be US$25 to 270 billion per year in 2100 under a 0.5 to 2.0 m GMSLR for 2005–2100. Anthoff et al. (2010) estimate the net present value of dike construction costs for 2005–2100 to be US$80 to 120 billion for 0.5 m GMSLR and US$900 to 1100 billion for a 2 m GMSLR, respectively.

The available global studies show that it is economically rational to protect large parts of the world's coastline during the 21st century against sea level rise impacts of increased coastal flood damage and land loss (Nicholls and Tol, 2006; Anthoff et al., 2010; Hinkel et al., 2013; *limited evidence*, *high agreement*). For dry land and wetlands loss, the FUND model shows that cost-benefit analysis would justify protecting 80% of the exposed coast in all but 15 countries under a GMSLR of 20 to 40 cm per century (Nicholls and Tol, 2006). Using the same method, Nicholls et al. (2008) show that under extreme GMSLR of up to 4 m in 2100, this fraction would drop to 30% to 50%. For coastal flooding, an application of DIVA shows that, for 21st century GMSLR scenarios of 60 to 126 cm, the global costs of protection through dikes (levees) are much lower than the costs of damages avoided through adaptation (Hinkel et al., 2013).

At the same time, costs and benefits of sea level rise impacts and adaptation vary strongly between regions and countries with some developing countries and small islands reaching limits of adaption or not being able to bear the costs of impacts and adaptation (*limited evidence*, *high agreement*) (Section 29.6.2.1). The cost of 1 m of GMSLR in 2100 (considering land loss due to submergence and protection costs) is projected to be above 1% of national GDP for Micronesia, Palau, the Bahamas, and Mozambique (Anthoff et al., 2010). For coastal flooding, annual damage and protection costs are projected to amount to several percentages of the national GDP for small island states such as Kiribati, the Solomon Islands, Vanuatu, and Tuvalu under GMSLR projections of 0.6 to 1.3 m by 2100 (Hinkel et al., 2013). Further substantial costs arise, particularly for developing countries owing to their current adaptation deficit (i.e., coastal defenses are not adapted to the current climate variability), which is not well understood and requires further analysis (Parry et al., 2009). For example, the adaption deficit of Africa with regard to coastal flooding is estimated at US$300 billion (Hinkel et al., 2011) and that of Bangladesh with respect to cyclones at US$25 billion (World Bank, 2011).

Several methodological gaps remain. As there are so few studies on the costs and benefits of sea level rise at a global level, uncertainties are largely unknown and the need for further research is great. The socioeconomic drivers, sea level rise scenarios, and impacts considered as well as damages and losses valued are incomplete. For example, costs of salinity intrusion, land loss due to increased coastal erosion, cost of forced migration due to permanent inundation, the backwater effect, and the impact of sea level rise in combination with other drivers on ecosystems have not been assessed at global scales (Section 5.5.5). Generally for sea level rise impacts, it is difficult to establish a "no adaptation" baseline and the choice of the baseline changes damage costs (Yohe et al., 2011).

Another gap is related to the fact that global studies have focused on protection via hard structures while many more potentially cheaper or socially preferable measures are available including "soft" protection, retreat, and accommodation measures (Section 5.1). Future work needs to consider trade-offs between all available measures. Hard protection measures, for example, may incur additional costs on adjacent unprotected coasts (Brown et al., 2013) or destroy coastal wetlands through coastal squeeze (Section 5.4.2.3). While the costs of "soft" protection measures such as ecosystem-based adaptation (EBA) are largely unknown (Linham and Nicholls, 2010; Engineers Australia, 2012), these may provide additional benefits in the form of a variety of ecosystem services (Alongi, 2008; IUCN, 2008; Anthony et al., 2009; Vignola et al., 2009; Pérez et al., 2010; Espinosa-Romero et al., 2011; McGinnis and McGinnis, 2011; Zeitlin et al., 2012). Finally, it must be noted that protection also further attracts people and development to the floodplain, which in turn increases the risk of potential catastrophic consequence in the case of defense failure. This is particularly true for many coastal cities such as London, Tokyo, Shanghai, Hamburg, and Rotterdam that already rely heavily on coastal defenses (Nicholls et al., 2007).

5.5.6. Adaptation Opportunities, Constraints, and Limits

There is a growing recognition of the potential co-benefits and new opportunities that can be achieved by mainstreaming adaptation with existing local to national goals and priorities (Section 14.3.4). DRR and adaptation share the common goals of reducing vulnerability against impacts of extreme events while creating strategies that limit risk from hazards (IPCC, 2012). This is especially true in coastal areas where extreme flooding events due to severe storm surges are one of the main sources of hazard. Besides, integrating adaptation with national and local planning can also contribute to building resilience in coastal areas.

EBA is considered to be an emerging adaptation opportunity (Munroe et al. 2011) (Section 16.6, Box CC-EA). In coastal areas, the conservation or restoration of habitats (e.g., mangroves, wetlands, and deltas) can provide effective measures against storm surge, saline intrusion, and coastal erosion by using their physical characteristics, biodiversity, and the ecosystem services they provide as a means for adaptation (Borsje et al., 2011; Jones et al., 2012; Cheong et al., 2013; Duarte et al., 2013b; see also Section 5.5.7).

Since AR4, a variety of studies have been published providing a better understanding of the nature of the constraints and limits to adaptation, both generally (Sections 16.3, 16.4) and more specifically in the coastal sector (e.g., Ledoux et al., 2005; Moser et al., 2008; Tribbia and Moser, 2008; Bedsworth and Hanak, 2010; Frazier et al., 2010; Saroar and Routray, 2010; Mozumber et al., 2011; Storbjörk and Hedrén, 2011; Lata and Nunn, 2012).

Constraints specific to coastal adaptation are polarized views in the community regarding the risk of sea level rise and concerns regarding the fairness of retreat schemes in Australia (Ryan et al., 2011); lack of awareness of sea level rise risks and spiritual beliefs in Fiji (Lata and Nunn, 2012); insufficient budget for the development of adaptation policies and other currently pressing issues in the USA (Tribbia and Moser, 2008; Mozumber et al., 2011); distinct preferences for retreat options depending on several social and exposure conditions in Bangladesh (Saroar and Routray, 2010); and the need to provide compensatory habitats under the Habitats Regulations and lack of local public support in the UK (Ledoux et al., 2005). Other relevant constraints include the lack of locally relevant information, resource tenure, and political will, especially critical in developing countries (*robust evidence*, *high agreement*). Besides, a gap exists between the useful climate information provided by scientists and the one demanded by decision makers.

Different constraints typically do not act in isolation, but in interacting bundles (*robust evidence*, *high agreement*). Therefore it is difficult to predict which constraints matter most in any specific context but instead multiple constraints need to be addressed if adaptation is to move successfully through the different stages of the management process (Moser and Ekstrom, 2010; Londsdale et al., 2010; Storbjörk, 2010; *medium evidence*, *high agreement*). Besides, some factors can act as enablers and add to the adaptation capacity, while acting as constraints for others (Burch, 2010; Storbjörk, 2010; *medium evidence*, *high agreement*).

Finally, a common concern emerging from the literature reviews (Biesbroek et al., 2010; Ekstrom et al., 2011) is that some critical constraints arise from the interactions across policy domains, existing laws and regulations, and long-term impacts of past decisions and policies (*low evidence*, *high agreement*).

A limit is reached when adaptation efforts are unable to provide an acceptable level of security from risks to existing objectives and values and prevent the loss of key attributes, components, or services of an ecosystem (Box 16-1; Sections 16.2, 16.5) and may arise as a result of most of the constraints described above.

Regarding coastal areas, it is widely recognized that biophysical limitations arise, for example, in small island developing states where adaptation through retreat to increasing impact of sea level rise in conjunction with storm surges and flooding is not an option due to limited high land availability, creating a temporary and eventually permanent human displacement from low-lying areas (Pelling and Uitto, 2001; *medium evidence*, *high agreement*). Nicholls et al. (2011) show that only a limited number of adaptation options are available for specific coastal areas if sea level exceeds a certain threshold (1 m) at the end of the century.

Regarding natural (unassisted) adaptation, several researchers have examined biophysical limits, for example, of coastal marshes (Craft et al., 2009; Langley et al., 2009; Mudd et al., 2009; Kirwan et al., 2010), and found that under certain nonlinear feedbacks among inundation, plant growth, organic matter accretion, and sediment deposition coastal wetlands can adapt to conservative rates of sea level rise (SRES A1B) if suspended sediment surpasses a certain threshold. In contrast, even coastal marshes with high sediment supplies will submerge near the end of the 21st century under scenarios of more rapid sea level rise (e.g., those that include ice sheet melting).

Increased ocean acidification is expected to limit adaptation of coral reefs to climate change (Boxes CC-OA and CC-CR).

5.5.7. Synergies and Trade-offs between Mitigation and Adaptation

Klein et al. (2007, p. 749) defined trade-offs between mitigation and adaptation as the "balancing of adaptation and mitigation when it is not possible to carry out both activities fully at the same time (e.g., due to financial or other constraints)." Successful adaptive coastal management of climate risks will involve assessing and minimizing potential trade-offs with other non-climate policy goals (e.g., economic development, enhancement of coastal tourism) and interactions between adaptation and mitigation (e.g., Brown et al., 2002; Tol, 2007; Barbier et al., 2008; Bunce et al., 2010).

Adaptation will be the predominant approach to reducing climate risks to coastal communities, populations, resources, and activities over the 21st century as large increases in sea level rise cannot be ruled out (WGI AR5 Section 13.5.2) and because of the time lag between emissions reductions, temperature changes, and impacts on global sea levels (Nicholls et al., 2007, 2011; see also Section 5.5.7). Still, positive synergies and complementarities between mitigation and adaptation in the coastal sector exist.

Since AR4, a series of studies have pointed out that marine vegetated habitats (seagrasses, salt marshes, macroalgae, or mangroves) contribute to almost 50% of the total organic carbon burial in ocean sediments leading to the so-called Blue Carbon (coastal carbon stocks) strategies (Nellemann et al., 2009; McLeod et al., 2011; Duarte et al., 2013b). These strategies aim at exploring and implementing the necessary mechanisms allowing Blue Carbon to become part of emission and mitigation protocols along with other carbon-binding ecosystems such as rainforests (Nellemann et al., 2009). Besides, marine vegetated habitats provide additional functions including the buffering of impacts against storm surges and waves, soil preservation, raising the seafloor, and shelter for fish nursery or habitat protection (Alongi, 2002; Kennedy and Björk, 2009; Duarte et al., 2013b). Consequently, restoration or ecosystem engineering of marine vegetated areas can be considered as a good example of positive synergies between adaptation and mitigation in coastal areas (Borsje et al., 2011; Jones et al., 2012; Duarte et al., 2013b) and should be further explored to be considered as a valid alternative in the portfolio of measures for climate change mitigation and adaptation. Only recently results have been presented on the role of a 1700 ha seagrass restoration in carbon storage in sediments of shallow coastal ecosystems in Virginia (USA). Restored seagrass meadows are expected to accumulate carbon at a rate comparable to ranges measured in natural seagrass meadows within 12 years of seeding, providing an estimated social cost of US$4.10 ha^{-1} yr^{-1} (Greiner et al., 2013).

Many coastal zone-based activities and various coastal management strategies involve emissions of GHGs. Reduction or cessation of some of them may have positive implications for both mitigation and adaptation. Limiting offshore oil production may imply a net reduction in GHG emissions depending on what form of energy replaces it, but also a reduced risk of oil spills, a reduction of stresses on the marine/coastal ecosystems, and variable socioeconomic impacts on human communities and public health (O'Rourke and Connolly, 2003). This may result in reduced vulnerability or increased resilience and consequently could prove positive for adaptation. However, this measure would increase the vulnerability of countries whose economies are highly dependent on oil extraction.

Some coastal adaptation options may have potentially negative implications on mitigation. Relocation of infrastructure and development out of the coastal floodplains (retreat) will imply increase in one-time GHG emissions due to rebuilding of structures and possible increase in low-density urban development and ongoing transportation-related emissions (Biesbroek et al., 2010). The building or upgrading of coastal protection structures or ports will also imply an increased energy use and GHG emissions related to construction (e.g., cement production) (Boden et al., 2011).

Similarly, actions beneficial for mitigation may result in potential negative impacts for adaptation. A more compact coastal urban design, increasing development in floodplains (Giridharan et al., 2007), or the development of marine renewable energy (Boehlert and Gill, 2010) may introduce additional drivers on coastal systems reducing coastal resilience and adaptive capacity.

5.5.8. Long-Term Commitment to Sea Level Rise and Adaptation

In AR4, both WGI and WGII highlighted the long-term commitment to sea level rise (Meehl et al., 2007; Nicholls et al., 2007), which means that sea levels will continue to rise for centuries due to global warming until reaching equilibrium conditions even if climate forcing is stabilized, because there is a delay in the response of sea level rise to global warming (WGI AR5 Section13.4.1). WGI AR5 has now assessed GMSLR until 2500 and this shows that even with aggressive mitigation measures (RCP2.6), sea level continues to rise after 2100 (Table 5-1; see also WGI AR5 Sections 13.5.1, 13.5.4). With more moderate (RCP4.5.) and little (RCP8.5) mitigation, larger ongoing increases in sea level are expected, lasting for several centuries. Note that the ranges given after 2100 are only model spread and not likely ranges. Looking beyond 2500, Levermann et al. (2013) project that GMSL will rise on average by about 2.3 m per degree Celsius of global warming within the next 2000 years. Under present levels of global warming, this means that we have already committed to a long-term sea level rise of 1.3 m above current levels (Strauss, 2013). For other climate-related drivers, responses to global warming levels are more immediate. For ocean acidification, for example, pH rise would cease several decades after strict CO_2 emission reductions begin (Bernie et al. 2010; see also Section 19.7.1).

This long-term commitment to sea level rise means that there is also a long-term commitment to sea level rise impacts and adaptation. Few studies have considered this and, from a methodological point of view, it is difficult to look at socioeconomic conditions and human responses on such large temporal scales. A limited number of studies have estimated the effects of mitigation on coastal impacts on human settlements and adaptation for the 21st century (Section 5.4.3.1). These studies show that despite the delayed response of sea level rise to global warming, mitigation can reduce impacts significantly already during the 21st century. These studies also show that for most urban areas, coastal protection is cost-efficient in reducing impacts during the 21st century (Section 5.5.5). Past and current adaptation practice also confirms this: cities such as Tokyo and Shanghai have protected themselves against local sea level rise of several meters during the 20th century and the Dutch and UK governments have decided that they can protect urban Netherlands and London against 21st century sea level rise above 1 m (Section 5.5.4). Not protecting cities such as Amsterdam, Rotterdam, and London during the 21st century is not an option. On the other hand, there are coastal areas such as small islands where protecting against several meters of sea level rise in the long term is not a viable option. Failing to mitigate, thus increasingly commits us to a world where densely populated areas lock into a trajectory of increasingly costly hard defenses and rising residual risks on the one hand and less densely populated areas being abandoned on the other hand. Mitigation thus plays, in the long term, a very important role in avoiding climate change impacts in coastal areas by reducing the rate of sea level rise and providing more time for long-term strategic adaptation measures to be adopted. However, even if anthropogenic CO_2 emissions were reduced to zero, sea levels would continue to rise for centuries, making adaptation in coastal areas inevitable.

5.6. Information Gaps, Data Gaps, and Research Needs

This chapter has updated knowledge on the impacts of climate change on the coastal systems not in isolation but also from the perspective of overexploitation and degradation that have been responsible for most of the historical changes. There is a better understanding of the varying impacts of weather and climate extremes and long-term sea level rise on human systems.

That sea levels will rise is a confident projection of climate science but uncertainties around the magnitude of future sea level rise remain large. The rates and magnitude of sea level rise are summarized in Table 5-1 but, under present levels of global warming, we are already committed to 1.3 m future sea level rise above current levels (Section 5.5.8). However, many sea level rise assessments are not provided at spatial or temporal scales most relevant for decision makers who require information on baseline conditions and projections of change (Kettle, 2012) of RSLR (i.e., including local subsidence) for vulnerability assessment and adaptation planning.

Generally, quantitative predictions of future coastal change remain difficult despite the application of improvements in technology—for example, aerial photographs, satellite imagery, Light Detection And Ranging (LiDAR; Sesil et al., 2009; Revell et al., 2011; Pe'eri and Long, 2012)—to investigate and characterize large-scale shoreline changes. There is incomplete understanding of coastal changes over the decade and century time scales (Woodroffe and Murray-Wallace, 2012). Shoreline response is more complex than simple submergence because of factors such as sediment supply, mobilization and storage, offshore geology, engineering structures, and wave forcing (Ashton et al., 2011). The projection of the future impacts of climate change on natural systems is often hampered by the lack of sufficiently detailed data at the required levels of space and time. Although observations have been made on impacts on beaches, rocky coasts, wetlands, coastal aquifers, delta areas, or river mouths by multi-drivers of climate and human-induced origin, there is still an incomplete understanding of the relative role played by each of these drivers and, especially of their combined effect. Uncertainties are even higher when it comes to the evaluation of projected impacts.

For coastal ecosystems, more work needs to be done to develop predictive models based on findings from multi-stressor experiments, both in the field and in the laboratory. Reliable predictions require information on multifactorial experiments performed on communities (preferably in the field), and on time scales of months to years in order to take into consideration the processes of biological acclimation and adaptation.

Although sea level is projected to rise in the future, there are significant gaps in vulnerability assessment of other specific coastal impacts. For example, the modeling of diseases that could affect coastal areas is based mainly on the mean values of climate. Also, despite tourism being one of the most important industries in the coastal areas, not enough is known about tourists' reactions to projected climatic change (Moreno and Amelung, 2009b) or required adaptation measures for port facilities (UNCTAD, 2009).

A wide range of coastal management frameworks and measures is available and used in coastal adaptation to climate change, and the scope for their integration has increased by combining scenarios of climate change and socioeconomic conditions and risk assessment (Kirshen et al., 2012). While various adaptation measures are available, at the local level, there remains insufficient information on assessment of adaptation options, particularly in developing countries.

Data and knowledge gaps exist or their reliability is insufficient. Despite the availability of potentially useful climate information, a gap exists between what is useful information for scientists and for decision makers. For example, at the project level, engineers may have difficulties to "plug in" climate projections presented by scientists. The proposed actions to improve usability include varying levels of interaction, customization, value-adding, retailing, and wholesaling (Lemos et al., 2012) so that data and methods can be more openly accessible to fellow scientists, users, and the public (Kleiner, 2011).

Coastal systems are affected by human and climate drivers and there are also complex interactions between the two. In general, certain components of coastal systems are sensitive and attributable to climate drivers while others are not clearly discernible. For example, data are available on the range shift in coastal plant and animal species and the role of higher temperatures on coral bleaching (see Box CC-CR). However, in many cases in the human systems, the detectable changes can be largely attributed to human drivers (Section 5.3.4). Reducing our knowledge gaps on the understanding of the processes inducing changes would help to respond to them more efficiently.

The economics of coastal adaptation are under-researched. More comprehensive assessments of valuation of coastal ecosystem services, adaptation costs, and benefits that simultaneously consider both the gradual impact of land loss due to sea level rise and the stochastic impacts of extreme water levels (storm surges, cyclones) are needed, as well as other impacts such as saltwater intrusion, wetlands loss and change, and backwater effects. Assessments should also consider a more comprehensive range of adaptation options and strategies, including "soft" protection, accommodation, and retreat options as well as the trade-offs between these.

Governance of coastal adaptation and the role of institutions in the transition toward sustainable coasts are under-researched. While institutional factors are recognized to be decisive in constraining and enabling coastal adaptation, most work remains descriptive. There is a great need for dedicated social science research aimed at understanding institutional change and which institutional arrangements are effective in which socioeconomic and biophysical contexts (Kay, 2012; see also Sections 5.5.3, 5.5.4).

Developing a coastal adaptation knowledge network between scientists, policymakers, stakeholders, and the general public could be considered a priority area for large coastal areas or regional areas affected by climate change and sea level rise. This is well developed in the USA, European Union, the Mediterranean, and Australia but less so in the developing countries, except in certain regions, for example, Caribbean islands and the Pacific Islands.

Future research needs for coastal adaptation are identified by several developments in climate science. Based on the Li et al. (2011) survey of the foci of climate research in the 21st century, the implications for coasts would be on biodiversity and flooding. Future technological advances may be significant—for example, new forms of energy and food production and information and communication technology (ICT) for risk monitoring (Delta Commission, 2008; Campbell et al., 2009; Zevenbergen et al., 2013)—and these would be useful for flood risks and food production in deltas and coastal systems (aquaculture).

With recent adverse climatic and environmental events on coasts, adaptation demands different decision regimes (Kiker et al., 2010) but adaptation, mitigation, and avoidance measures still require integrating research that includes natural and social sciences (CCSP, 2009). Although many gaps still remain, there is nevertheless a greater foundation of climate change research on coasts across a wide range of fields (Grieneisen and Zhang, 2011) upon which scientists, policymakers, and the public may find improved solutions for coastal adaptation.

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6 Ocean Systems

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Executive Summary

Ocean ecosystems have responded and will continue to respond to climate changes of different rates, magnitudes, and durations (*virtually certain*). Human societies depend on marine ecosystem services, which are sensitive to climate change (*high confidence*), in particular the provisioning of food (fisheries and aquaculture) and other natural resources; nutrient recycling; regulation of global climate including production of oxygen (O_2) and removal of atmospheric carbon dioxide (CO_2); protection from extreme weather and climate events; and aesthetic, cultural, and supporting services. {6.3, 6.4, 6.5}

Climate change alters physical, chemical, and biological properties of the ocean (*very high confidence*). Oceanic drivers include salinity, circulation, temperature, carbon dioxide (CO_2), oxygen (O_2), nutrients, and light. These drivers shape the physiological performance of individual cells and organisms and ultimately determine ecosystem composition, spatial structure, and functioning. {6.1.1, 6.3}

The fossil record and present field and laboratory observations confirm links between key environmental drivers and responses of ocean ecosystems to climate change (*high confidence*). For millions of years in Earth history, natural climate change at rates slower than today's anthropogenic change has led to significant ecosystem shifts (*high confidence*), including species emergences and extinctions (*high confidence*). Contemporary multi-decadal natural climate variations associated with regional transient warming periods by 1°C have led to fundamental restructuring of ecosystems and large socioeconomic implications (*high confidence*). {6.1.2, 6.3.1, 6.4}

Vulnerability of most organisms to warming is set by their physiology, which defines their limited temperature ranges and hence their thermal sensitivity (*high confidence*). Temperature defines the geographic distribution of many species and their responses to climate change. Shifting temperature means and extremes alter habitat (e.g., sea ice and coastal), and cause changes in abundance through local extinctions and latitudinal expansions or shifts (*very high confidence*). Vulnerability is greatest in polar animals owing to their narrow temperature ranges (*medium confidence*) and in tropical species living close to upper thermal limits (*medium confidence*). Although genetic adaptation occurs (*medium confidence*), the capacity of present-day fauna and flora to compensate for or keep up with the rate of ongoing thermal change is limited (*low confidence*). {6.3.1, 6.3.5, 6.5.2}

The warming-induced shifts in the abundance, geographic distribution, migration patterns, and timing of seasonal activities of species (*very high confidence*) have been and will be paralleled by a reduction in their maximum body size (*medium confidence*). This has resulted and will further result in changing interactions between species, including competition and predator-prey dynamics (*high confidence*). Numerous observations over the last decades in all ocean basins show global-scale changes including large-scale distribution shifts of species (*very high confidence*) and altered ecosystem composition (*high confidence*) on multi-decadal time scales, tracking climate trends. The distribution and abundance of many fishes and invertebrates have shifted poleward and/or to deeper, cooler waters (*high confidence*). Poleward displacements of phyto- and zooplankton have occurred by hundreds of kilometers per decade (*high confidence*). Some warm-water corals and their reefs have responded with species replacement, bleaching, and a decreased coral cover causing habitat loss (*high confidence*). While marine reptiles such as turtles encounter direct effects of warming, impacts to seabirds and marine mammals are mostly indirect through effects of warming on their prey (*high confidence*). {6.3.1, 6.3.7, 6.5, Boxes CC-CR, CC-MB}

In response to further warming by 1°C or more by the mid-21st century and beyond, ocean-wide changes in ecosystem properties are projected to continue (*high confidence*). Large irreversible shifts in the spatial distribution of species and seasonal timing of their activities (feeding, growth, development, behaviors, and productivity) will have implications for species composition, and ecosystem goods and services. {6.3.1, 6.4, 6.5, 6.6}

By the mid-21st century, the spatial shifts of marine species will cause species richness to increase at mid- and high latitudes (*high confidence*) and to decrease at tropical latitudes (*medium confidence*), resulting in global redistribution of catch potential for fishes and invertebrates, with implications for food security (*medium confidence*). Animal displacements are projected to lead to high-latitude invasions and high local extinction rates in the tropics and semi-enclosed seas. This will cause a 30 to 70% increase in the fisheries yield of some high-latitude regions by 2055 (relative to 2005), a redistribution at mid-latitudes, but a drop of 40–60% in the tropics and the Antarctic, based on 2°C warming above preindustrial values (*medium confidence* in the direction of trends in fisheries yields, *low confidence* in the magnitude of change). If a decrease in global net primary production (NPP) or a shift toward smaller primary producers occurs, the overall fisheries catch potential may also decrease. {6.3.1-4, 6.4.1, 6.5.1-4}

Open ocean NPP is projected to fall globally depending on RCP scenario (*medium confidence*). The estimated decrease will occur by up to 9% by 2100 under the RCP8.5 business-as-usual climate scenario (relative to 1990, *low confidence*). The oceans currently provide about half of global NPP. Environmental controls on NPP include temperature, CO_2, nutrient supply, and light (through cloud cover, mixed layer depth), all of which will be altered (WGI AR5 Section 6.3). Present observations indicate increasing NPP at high (Arctic) latitudes (*medium confidence*), projected to continue beyond 2100 (*medium confidence*). This increase is offset by a decrease at temperate and tropical latitudes (*medium confidence*). Poor representation of shelf and coastal regions hamper projections in global NPP models for near-shore waters, reducing confidence in global projections. {6.3.4, 6.5.1, Box CC-PP}

Large-scale processes and climatic feedbacks sustained by microbes (bacteria, archaea, unicellular algae, and protozoans) play key roles in marine ecosystems (e.g., carbon and nitrogen (N_2) fixation or nutrient recycling) and will be altered by climate change (*medium confidence*). Identifying which microbial species, groups, and processes are being affected and how these will be altered is difficult, as these organisms and their responses to environmental change are extremely diverse and often modulated by biological interactions or changes in circulation and nutrient supply (*limited evidence*, *low agreement*). Warming will cause species-specific responses, such as enhancing metabolic rates and exceeding thermal tolerances, which will affect abundance, distribution, and community structure. Warmer, CO_2- and nutrient-enriched coastal oceans may stimulate harmful algal blooms (*medium confidence*), and the redistribution of certain microbes causing diseases such as cholera (*medium confidence*). {6.3, 6.4.2}

Rising atmospheric CO_2 over the last century and into the future not only causes ocean warming but also changes carbonate chemistry in a process termed ocean acidification (WGI AR5 Sections 3.8.2, 6.4.4). Impacts of ocean acidification range from changes in organismal physiology and behavior to population dynamics (*medium* to *high confidence*) and will affect marine ecosystems for centuries if emissions continue (*high confidence*). Laboratory and field experiments as well as field observations show a wide range of sensitivities and responses within and across organism phyla (*high confidence*). Most plants and microalgae respond positively to elevated CO_2 levels by increasing photosynthesis and growth (*high confidence*). Within other organism groups, vulnerability decreases with increasing capacity to compensate for elevated internal CO_2 concentration and falling pH (*low* to *medium confidence*). Among vulnerable groups sustaining fisheries, highly calcified corals, mollusks, and echinoderms are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*). Trans-generational or evolutionary adaptation has been shown in some species, reducing impacts of projected scenarios (*low* to *medium confidence*). Limits to adaptive capacity exist but remain largely unexplored. {6.3.2, Box CC-OA}

Few field observations conducted in the last decade demonstrate biotic responses attributable to anthropogenic ocean acidification, as in many places these responses are not yet outside their natural variability and may be influenced by confounding local or regional factors. Shell thinning in planktonic foraminifera and in Southern Ocean pteropoda has been attributed fully or in part to acidification trends (*medium* to *high confidence*). Coastward shifts in upwelling CO_2-rich waters of the Northeast Pacific cause larval oyster fatalities in aquacultures (*high confidence*) or shifts from mussels to fleshy algae and barnacles (*medium confidence*), providing an early perspective on future effects of ocean acidification. This supports insight from volcanic CO_2 seeps as natural analogs that macrophytes (seaweeds and seagrasses) will outcompete calcifying organisms. During the next decades ecosystems, including cold- and warm-water coral communities, are at increasing risk of being negatively affected by ocean acidification, especially as ocean acidification will be combined with rising temperature extremes (*medium* to *high confidence*, respectively). {6.1.2, 6.3.2, 6.3.5}

The expansion of hypoxic regions termed Oxygen Minimum Zones (OMZs) and anoxic "dead zones," observed over the last 50 years and projected into the future under climate change, especially if combined with nutrient enrichment (eutrophication), will constrain the habitat of O_2-dependent organisms and benefit anaerobic microbes (*medium confidence*). Hypoxia tolerance varies among species and is influenced by temperature, elevated CO_2, food consumption, and O_2 demand (*high confidence*). Warming-induced stratification limits the exchange of gases between water layers. Enhanced oxygen consumption by heterotrophic organisms depletes the oxygen further, causing a community shift toward lower species richness and hypoxia-tolerant specialists. Under extreme hypoxia ecosystems are dominated by microbes. These OMZs are also characterized by microbial removal of fixed nitrogen (denitrification), which can significantly reduce the low-latitude nutrient inventories with implications for regional productivity. {6.3.3, 6.3.5}

The climate-change-induced intensification of ocean upwelling in some eastern boundary systems, as observed in the last decades, may lead to regional cooling rather than warming of surface waters and cause enhanced productivity (*medium confidence*), but also enhanced hypoxia, acidification, and associated biomass reduction in fish and invertebrate stocks. Owing to contradictory observations there is currently uncertainty about the future trends of major upwelling systems and how their drivers (enhanced productivity, acidification, and hypoxia) will shape ecosystem characteristics (*low confidence*). {6.1.1, 6.3.2, 6.3.3, 6.3.5-6, Box CC-UP}

Environmental drivers acting simultaneously on ocean biota* often lead to interactive effects and complex responses (*high confidence*). Interactions of temperature, ocean acidification, and hypoxia narrow thermal ranges and enhance sensitivity to temperature extremes in organisms such as corals, coralline algae, mollusks, crustaceans, and fishes (*high confidence*). In primary producers, light and individual nutrients can also interact with temperature and acidification. Combined warming and ocean acidification reduce calcification in warm-water corals (*high confidence*). Ocean acidification will alter availability of trace metals (*low confidence*). (*The term biota encompasses the organisms of a region, habitat, or geological period.) {6.3.2.2, 6.3.5, 6.5.2}

The combination and often amplification of global and regional climate change and local anthropogenic drivers result in enhanced vulnerability of natural and human systems (*high confidence*). Major regional and local drivers include fishing, pollution, and eutrophication. {6.3.5, 6.4, 6.5}

The progressive redistribution of species and the reduction in marine biodiversity in sensitive regions and habitats puts the sustained provision of fisheries productivity and other ecosystem services at risk, which will increase due to warming by 1°C or more by 2100 compared to the present (*high confidence*). Human societies respond with limited adaptive capacity. Socioeconomic vulnerability is highest in developing tropical countries involving a risk of reduced supplies, income, and employment from marine fisheries (*high confidence*). This emphasizes disparities in food security between developed and underdeveloped nations. {6.4.1, 6.5}

With continuing climate change, local adaptation measures (such as conservation) or a reduction in human activities (such as fishing) may not sufficiently offset global-scale effects on marine ecosystems (*high confidence*). Effects of climate change will thus complicate management regimes such as of marine protected areas once species undergo distributional shifts. This increases the vulnerabilities of marine ecosystems and fisheries. {6.4.2.1}

Geoengineering approaches involving manipulation of the ocean to ameliorate climate change (such as nutrient fertilization, binding of CO_2 by enhanced alkalinity, or direct CO_2 injection into the deep ocean) have very large environmental and associated socioeconomic consequences (*high confidence*). Some actually require purposeful alteration of ocean ecosystems for implementation. Alternative methods focusing on solar radiation management (SRM) leave ocean acidification largely unabated as they cannot mitigate CO_2 emissions. {6.4.2}

6.1. Introduction: Point of Departure, Observations, and Projections

The oceans cover about 71% of Earth's surface to an average depth of 3700 m. Their importance for life on Earth, including humans, is vast (FAQ 6.1). Marine habitats display natural variability on various spatial and temporal scales but a dearth of long-term observational data from the vast open oceans limits our understanding of the causes and ecological consequences of this variability. The available information indicates that climate controls ocean temperatures, chemistry, circulation, upper ocean stratification, nutrient supply, and sunlight exposure. These drivers affect marine ecosystems through direct effects on organisms, amplified by their changing interactions with other species. Food webs are modified by changes in phytoplankton growth and the availability of live organisms or their decomposing bodies, that is, debris or dissolved organic matter, as food to (chemo-)heterotrophs (organisms gaining energy by feeding on organic matter). Organismal responses lead to changes in biogeochemical processes, such as the carbon cycle, and in biological diversity and the services the oceans provide.

Some impacts of climate change on marine ecosystems and their services were addressed in the IPCC Fourth Assessment Report (AR4): WGII Chapters 4 to 6 (ecosystems, food, coastal areas), and regional chapters, for example, 15 (polar regions) and 16 (small islands). The ecosystem assessment in WGII AR4 Chapter 4 focused on terrestrial, coastal, and marine systems, their properties, goods, and services. It emphasized the difficulty in assessing future ecosystem responses as a result of ecosystem complexity, different vulnerabilities of species, and ecosystem-specific, critical thresholds associated with nonlinear responses to environmental change. Focusing on terrestrial ecosystems, WGII AR4 Chapter 4 concluded that more than 2°C to 3°C warming above preindustrial levels causes high extinction risks to 20 to 30% of present-day species (*medium confidence*), paralleled by substantial changes in ecosystem structure and functioning (*high confidence*). The authors projected that a wide range of planktonic and benthic calcifiers will be impacted by ocean warming (*very high confidence*) and acidification (*medium confidence*), particularly in the Southern Ocean. They characterized sea ice and coral reef biomes as highly vulnerable. Key uncertainties identified in AR4 were the incomplete knowledge of ocean acidification (addressed in present Section 6.3.2), synergistic effects and their mechanisms (Section 6.3.5), biotic feedbacks to the climate system (Section 6.4), and the impacts of interactions between climate change, human uses, and ecosystem management (Section 6.4.2).

Much more than in previous IPCC reports (Figure 1-2), impacts on the oceans are a focus in AR5. This allows for a more comprehensive discussion of phenomena and impacts, as well as the associated uncertainties and the levels of confidence in observed and projected changes. The present chapter focuses on the general principles and processes characterizing climate change impacts on ocean systems and on the uses of these systems by human societies. For projections of responses to climate change, the chapter also assesses our understanding of underlying functional mechanisms causing change across all levels of biological organization, from molecules to organisms to ecosystems. As the ocean is a heterogeneous environment, the comparison of major ocean regions is required to understand variability and differences in key processes and carbon inventories (Box CC-PP, Figure 1). We discuss the changes and variability in the ocean's principal physical and chemical properties and assess knowledge drawn from paleo- and historical to present observations. We develop a conceptual framework for analyzing

Frequently Asked Questions

FAQ 6.1 | Why are climate impacts on oceans and their ecosystems so important?

Oceans create half the oxygen (O_2) we use to breathe and burn fossil fuels. Oceans provide about 17% of the animal protein consumed by the world's human population, or almost 20% of that protein consumed by 3 billion people. Oceans are home to species and ecosystems valued in tourism and for recreation. The rich biodiversity of the oceans offers resources for innovative drugs or biomechanics. Ocean ecosystems such as coral reefs and mangroves protect the coastlines from tsunamis and storms. About 90% of the goods the world uses are shipped across the oceans. All these activities are affected by climate change.

Oceans play a major role in global climate dynamics. Oceans absorb 93% of the heat accumulating in the atmosphere, and the resulting warming of oceans affects most ecosystems. About a quarter of all the carbon dioxide (CO_2) emitted from the burning of fossil fuels is absorbed by oceans. Plankton convert some of that CO_2 into organic matter, part of which is exported into the deeper ocean. The remaining CO_2 causes progressive acidification from chemical reactions between CO_2 and seawater, acidification being exacerbated by nutrient supply and with the spreading loss of O_2 content. These changes all pose risks for marine life and may affect the oceans' ability to perform the wide range of functions that are vitally important for environmental and human health.

The effects of climate change occur in an environment that also experiences natural variability in many of these variables. Other human activities also influence ocean conditions, such as overfishing, pollution, and nutrient runoff via rivers that causes eutrophication, a process that produces large areas of water with low oxygen levels (sometimes called "dead zones"). The wide range of factors that affect ocean conditions and the complex ways these factors interact make it difficult to isolate the role any one factor plays in the context of climate change, or to identify with precision the combined effects of these multiple drivers.

effects on organisms and ecosystems and assess present knowledge derived from experiments, field studies, and numerical model projections mostly using Representative Concentration Pathways (RCPs) of climate change scenarios to provide trajectories of climate change drivers (Moss et al., 2010). Finally, we assess the implications of such changes for ecosystem services, and identify plausible socioeconomic consequences.

Assessing climate change impacts on coastal systems is the topic of Chapter 5. An integrative treatment of regional climate changes and impacts in seven key ocean regions is the focus of regional Chapter 30. Marine issues are also included in regional Chapters 22 to 29, with a focus on polar oceans (Chapter 28) and small islands (Chapter 29). Topics important to several chapters, such as ocean acidification, upwelling systems, primary productivity, changes in biogeography, and coral reefs, are discussed in joint assessments presented in the respective cross-chapter boxes.

6.1.1. Changes in Physical and Chemical Variables

Trends in ocean conditions over the last 60 years reflect significant human impacts beyond natural variability on temperature, salinity, dissolved inorganic carbon and oxygen content, pH, and other properties of the upper ocean (e.g., Pierce et al., 2012; Sen Gupta and McNeil, 2012; WGI AR5 Section 3.8, Table 10.1). With climate change, marine ecosystems are and will be exposed to rising temperature, ocean acidification, expansion of hypoxic zones, and other environmental drivers changing concomitantly.

6.1.1.1. Temperature and Salinity

Over the last 39 years, oceans have warmed at average rates of >0.1°C per decade in the upper 75 m and 0.015°C per decade at 700 m depth (WGI AR5 Section 3.2.2, Figure 3.1). Trends differ regionally, seasonally, and interannually (WGI AR5 Section 2.7; for ocean regions see Section 30.5 in the present volume). Temperature changes are particularly large at El Niño-Southern Oscillation (ENSO) with high (3- to 4-year) and low (5- to 7-year) frequencies, and on multi-decadal scales (>25 years, Figure 6-1). The strongest warming trends are found at high latitudes where most of the inter-decadal variability occurs, while tropical oceans are dominated by interannual frequencies. Global climate models have explored changes in different frequency domains, but their spatial resolution is poor (WGI AR5 Sections 11.3.3, 12.4.7).

Temperature variations are often accompanied by changes in salinity. Increased salinity results from reduced precipitation relative to evaporation, for example, above the thermoclines (layer separating the upper mixed layer from deeper water where temperature and density change rapidly with depth) of subtropical gyres at mid- to low latitudes since 1950 (WGI AR5 Chapter 3). Decreased salinity due to enhanced precipitation relative to evaporation has occurred at some tropical and higher latitudes, exacerbated by sea ice melt (Durack et al., 2012). Both warming and freshening cause enhanced density stratification, a trend projected to continue into the 21st century (WGI AR5 Chapter 3, Section 11.3.3, Figure 12.34; Helm et al., 2010). Mean sea surface temperature in 2090 will be 2.7°C warmer than in 1990 (RCP8.5; WGI AR5 Chapter 12; Bopp et al., 2013).

6.1.1.2. Carbon Dioxide-induced Acidification

Rising carbon dioxide (CO_2) concentrations in air (given as partial pressures, *p*CO2, in μatm) cause increasing upper ocean CO_2 levels (Watson et al., 2009). Starting from a preindustrial value of 280 μatm atmospheric pCO_2 levels will have reached around 500 μatm by 2050 following the Special Report on Emissions Scenarios (SRES; IPCC, 2000) and all RCPs (Moss et al., 2010; Meinshausen et al., 2011). By 2100 values are projected to reach between 420 μatm and 940 μatm depending on the RCP. The rise in pCO_2 causes ocean acidification (OA), measured as a decline in water pH (negative log of proton concentration), accompanied by a fall in both carbonate ion (CO_3^{2-}) concentration and the saturation states (Ω) of various calcium carbonates ($CaCO_3$; Zeebe and Westbroek, 2003; WGI AR5 Section 3.8.2, Box 3.2, Chapter 6, Figure 6.29). Hence, the seawater solubilities of three forms of $CaCO_3$, namely calcite, magnesium-calcite, and aragonite, increase. These minerals are important components of shells and skeletons of many marine organisms (Section 6.3.2).

Ocean acidification occurs on a background of natural temporal and spatial variability of pH, pCO_2, and Ω. In the open ocean, the mean pH (total scale, pH_T) of surface waters presently ranges between 7.8 and 8.4 (WGI AR5 Section 3.8.2). In stratified mid-water layers, largely isolated from gas exchange between surface waters and air, decomposition of organic material leads to lowered oxygen (O_2) and elevated CO_2 levels (Paulmier et al., 2011) associated with lower pH values. The few existing field data of sufficient duration, resolution, and accuracy (WGI AR5 Figure 3.18) show that trends in anthropogenic OA clearly deviate from the envelope of natural variability (Friedrich et al., 2012). OA presently ranges between –0.0013 and –0.0024 pH_T units per year (WGI AR5 Section 3.8.2, Table 3.2, Box 3.2; Dore et al., 2009). Average surface ocean pH has decreased by more than 0.1 units below the preindustrial average of 8.17. By 2100 pH is expected to change by –0.13, –0.22, –0.28, and –0.42 pH_T units, at CO_2 levels of 421, 538, 670, and 936 ppm under RCP2.6, 4.5, 6.0, and 8.5 climate scenarios, respectively (WGI AR5 Figure 6.28). The rate of acidification in surface waters varies regionally and is 50% higher in the northern North Atlantic than in the subtropical Atlantic (Olafsson, 2009). Salinity reduction caused by ice melt or excess precipitation (Jacobs and Giulivi, 2010; Vélez-Belchí et al., 2010) exacerbates OA by diluting the concentrations of substances acting as buffers (Steinacher et al., 2009; Denman et al., 2011). At high sustained CO_2 concentrations the changes in ocean chemistry will take thousands of years to be buffered by the natural dissolution of $CaCO_3$ from sediments and tens to hundreds of thousands of years to be eliminated completely by the weathering of rocks on land (Archer et al., 2009).

6.1.1.3. Hypoxia

The average dissolved oxygen concentration in the ocean is presently 162 μmol kg^{-1} (Sarmiento and Gruber, 2006). Concentrations range from over 500 μmol kg^{-1} in productive Antarctic waters super-saturated with oxygen (Carrillo et al., 2004) to zero in coastal sediments and in permanently anoxic deep layers of isolated water bodies, such as the Black Sea and the Cariaco Basin. Hypoxia results from oxygen depletion in excess of supply as in stratified water bodies (Section 6.1.1.2). Vast Oxygen Minimum Zones (OMZs) exist between less than 100 and more

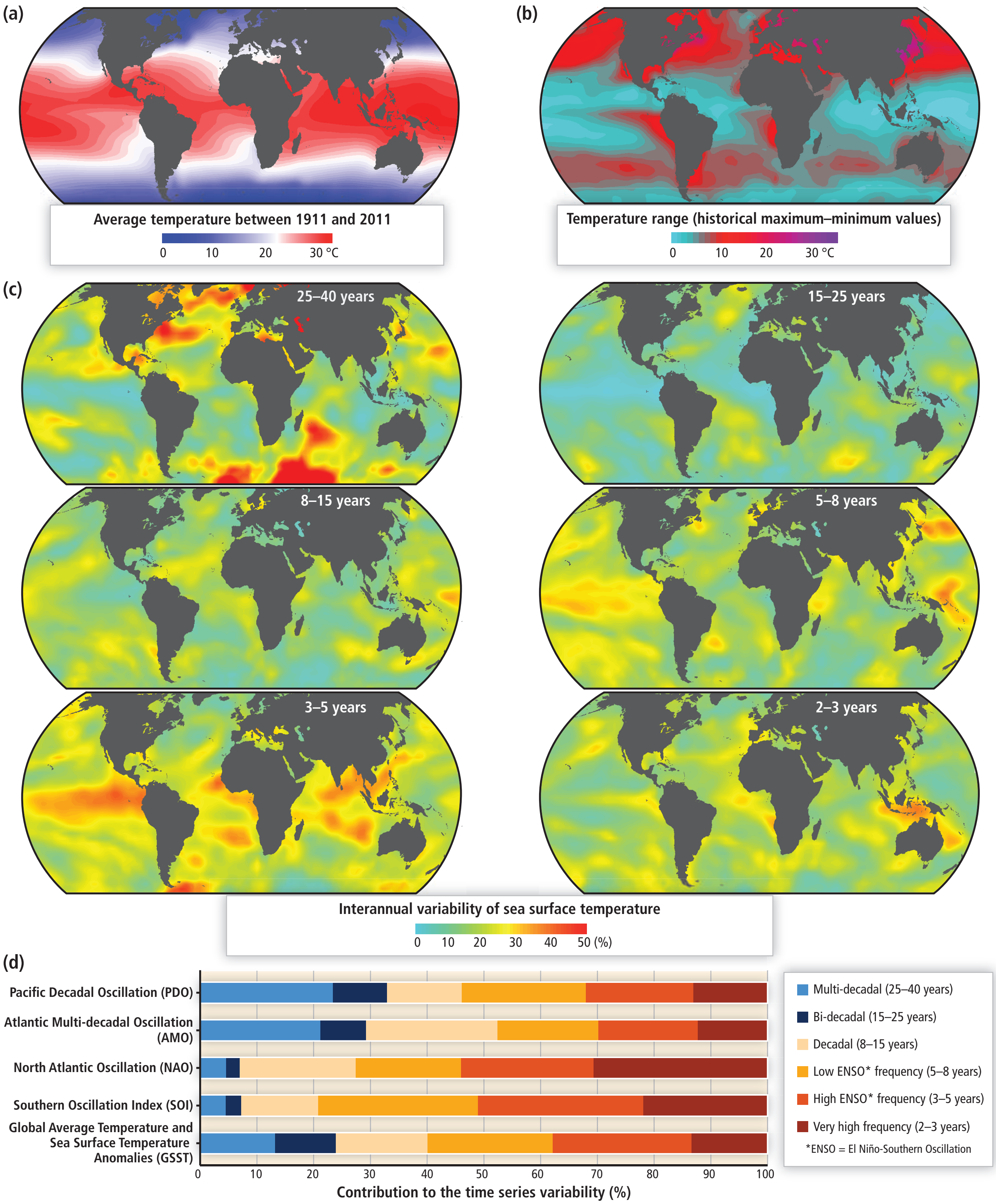

Figure 6-1 | Sea surface temperature variability between 1911 and 2011. (a) The sea surface temperature average for the period. (b) The temperature range calculated as the difference between the maximum and minimum values for each grid component during the century. (c) The spatial distribution of variability by time scales (based on the Extended Reynolds Sea Surface Temperature, NOAA, 2012) corresponds to the multi-decadal (25 to 40 years), bi-decadal (15 to 25 years), decadal (8 to 15 years), low ENSO (El Niño-Southern Oscillation) frequency (5 to 8 years), high ENSO frequency (3 to 5 years), and very high frequency (2 to 3 years) scales. The summed variabilities from the same 2°x2° box in all six maps corresponds to 100% of the time series variability. (d) The spectral density of some of the most widely used climate indices, accumulated in the same frequency windows. The total bar length (100%) corresponds to the cumulative variability of each time series between the 2 and 40 year frequency window. Climate indices were obtained from the NOAA ESRL Physical Sciences Division website.

6

than 900 m depths in Eastern Atlantic and Pacific tropical oceans. The ecological literature applies the term hypoxia (see Section 6.3.3) to O_2 concentrations below 60 µmol kg^{-1} (estimated at about 5% of global ocean volume; Deutsch et al., 2011). Pacific OMZs regularly reach oxygen levels below 20 µmol kg^{-1} (about 0.8% of global ocean volume; Paulmier and Ruiz-Pino, 2009), lower than Atlantic ones. Suboxic waters at <4.5 µmol O_2 kg^{-1} occupy about 0.03% of the ocean volume, mainly in the northeastern tropical Pacific (Karstensen et al., 2008).

OMZs are naturally present in many habitats including marine sediments, but are also expanding due to anthropogenic influences. Over the past 50 years, open ocean O_2 concentrations have decreased by a mean rate of 0.1 to >0.3 µmol kg^{-1} yr^{-1} (WGI AR5 Section 3.8.3; Stramma et al., 2008). In some OMZs the rate has been much higher due to warming, increased stratification, and rising biological O_2 demand (WGI AR5 Section 3.8.3). Long-term declines in O_2 by about 7 µmol kg^{-1} per decade have been documented at mid-water depths over much of the subarctic North Pacific (Keeling et al., 2010). In coastal regions, extremely hypoxic "dead zones" that exclude animal life, have increased from 42 reported in the 1960s to more than 400 in 2008 and been attributed to high oxygen demand from eutrophication, the local enrichment of nutrients, resulting in organic matter loading and its decay as well as nitrous oxide formation and release (Naqvi et al., 2000; Díaz and Rosenberg, 2008; Zhang et al., 2010).

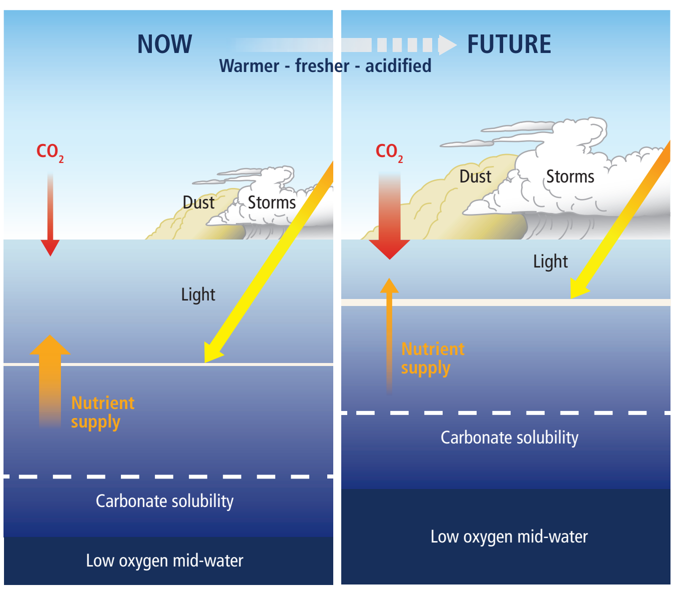

Figure 6-2 | Projected alteration (magnitude and frequency) of oceanic fluxes and atmospheric events due to a changing climate in the coming decades. Ocean properties will be altered from the sunlit surface layer to the mid-water stratum. In the surface ocean, the depth of the mixed layer (solid horizontal line) will shallow resulting in higher mean light levels. Increased density stratification (i.e., a strengthening sea water density gradient represented by the increasing thickness of the solid horizontal line) will reduce the vertical supply of nutrients for photosynthesizing organisms residing in the mixed layer. Anthropogenic CO_2 will acidify, that is, lower the pH of the surface ocean (note this happens in a pH range higher than 7 such that oceans will remain alkaline but less so due to acidification). The penetration of acidified waters to depth will result in a shallower depth (dashed horizontal line) at which $CaCO_3$ structures, such as shells, dissolve. At depth, the location of low-O_2 waters will progressively become shallower. In addition, changes in storm activity and dust deposition will influence ocean physics and chemistry, with consequent effects on ocean biota and hence ecosystems (courtesy of Reusch and Boyd, 2013).

Future warming will *likely* accelerate the spread of hypoxic zones, especially in temperate to sub-polar regions. Most models project decreasing global ocean oxygen contents by 1 to 7% from present-day concentrations in 2100 (Keeling et al., 2010; WGI AR5 Figure 6.30 under RCP8.5), with a mean decline by 3.4% in 2090 compared to the 1990s (Bopp et al., 2013). Warming and freshening of the surface layer will increase stratification and reduce the depth of winter mixing. The evolution of low O_2 zones will be linked to changes in fluvial runoffs (e.g. Milly et al., 2008; see also Section 5.3.4.3), the wind regime (e.g., Vecchi and Soden, 2007), as well as the intensity, duration, and seasonal timing of upwelling events (Snyder et al., 2003; see also Section 30.5.2). The potential contributions of destabilized methane hydrates and bacterial methane oxidation to exacerbate hypoxia and acidification at high latitudes remain to be explored (Westbrook et al., 2009). Currently, there is no consensus on the future volumes of hypoxic and suboxic waters because of large uncertainties in potential biogeochemical effects and in the evolution of tropical ocean dynamics due to both natural and anthropogenic causes (WGI AR5 Section 6.4.5). While volumes with O_2 concentrations <80 µmol kg^{-1} are projected to increase by several percent, suboxic waters <5 µmol O_2 kg^{-1} may undergo a 30% increase by 2100 compared to 2005 (*low confidence*; Bopp et al., 2013).

6.1.1.4. Light and Nutrients

Most models project that the mixed layer at the ocean surface (see Figure 6-2) will become shallower in the coming decades through a strengthening of the vertical density gradient (e.g., Sarmiento et al., 1998; Sallée et al., 2013). Mean light levels encountered by phytoplankton are set by incoming light from solar radiation, the depth of the mixed layer, and the degree to which underwater light is attenuated by living and non-living particles (Kirk, 1994). A shallower mixed layer will *likely* result in the resident phytoplankton receiving higher mean underwater light levels if the organisms are physically mixed through this stratum (Figure 6-2).

Enhanced, seasonally prolonged stratification (Holt et al., 2010), especially in the tropics, the North Atlantic, the Northeast Pacific, and the Arctic (Capotondi et al., 2012), will lead to decreased vertical transport of nutrients to surface waters (Doney, 2010; Figure 6-2). River plumes (Signorini et al., 1999), nutrient accumulation in the pycnocline as reported for North Pacific waters (Whitney, 2011), human-induced eutrophication, enhanced upwelling (Box CC-UP), and tidal mixing and estuarine circulation in coastal oceans could partly compensate for the projected reduction in nutrient supply in the oceans (*limited evidence*, *medium agreement*).

6.1.2. Historical and Paleo-Records

6.1.2.1. Historical Observations

Ocean ecosystems are variable in time and space, and in a non-steady-state, reflected in indices such as the North Atlantic Oscillation (NAO) Index, the Atlantic Multi-decadal Oscillation (AMO), the Arctic Climate Regime Index (ACRI), Pacific Decadal Oscillation (PDO), or the El Niño-Southern Oscillation (ENSO) (WGI AR5 Box 2.5; Figure 6-1; Section 30.5).

The combination of large, global data sets such as Reynolds, National Center for Atmospheric Research (NCAR), International Comprehensive Ocean-Atmosphere Data Set (ICOADS) with multi-decadal time series, for example, near Hawaii (HOT), Bermuda (BATS), the Ligurian Sea (DYFAMED), the Canaries (ESTOC), Kerguelen Island (KERFIX), Hokkaido Island (KNOT), and Taiwan (SEATS) has provided data on the physical and biogeochemical state of the oceans (Karl et al., 2003). These have been augmented by the limited-term, high-resolution programs World Ocean Circulation Experiment (WOCE) and Joint Global Ocean Flux Study (JGOFS).

Historical data sets provide baseline information on ecosystem states and document the responses of biota to both natural variability in the ocean system and surface ocean warming since the 1970s (Figure 6-3; Section 6.3.1). Such data sets are rare and regionally biased. Examples include changes in geographic ranges of plankton and seasonal timing (phenology) of different components of the ecosystem detected by the Continuous Plankton Recorder (CPR: e.g., Edwards et al., 2001; Richardson et al., 2006; Box 6-1) or multi-decadal shifts in pelagic ecosystems (CalCOFI) including higher parts of the food chain such as sardines and anchovies (Brinton and Townsend, 2003; Chavez et al., 2003; Lavaniegos and Ohman, 2003; see also Section 6.3.1) and the skeletal archives of long-lived organisms such as coralline algae (Halfar et al., 2011), bivalves (Schöne et al., 2003), and corals (De'ath et al., 2009).

Systematic, long-term interdisciplinary observations using repeated, highly calibrated measurements at a given field site are required to capture high- and low-frequency events, for example, regime shifts (abrupt changes between contrasting, persistent states of any complex system; deYoung et al., 2008). Direct observations are complemented by satellite remotely sensed data sets. Ocean color data (e.g., Coastal Zone Color Scanner (1978–1986), Sea-Viewing Wide Field-of-View Sensor (SeaWiFS, 1997–2010), and Moderate Resolution Imaging Spectroradiometer (MODIS-AQUA, 2002 to the present); McClain, 2009) provide estimates of chlorophyll concentrations (a proxy for phytoplankton stocks and net primary production (NPP); Sections 6.2.1, 6.3.4; Saba et al., 2011). Total chlorophyll cannot be measured from space; therefore, the near-surface value (approximately one optical depth) is extrapolated to whole water-column chlorophyll based on vertical distribution using region-specific algorithms. Large uncertainties persist, as these estimates reflect both phytoplankton stocks and their physiological status (Dierssen, 2010; Behrenfeld, 2011). The approximately 15-year archived time series of SeaWiFS is too short to reveal trends over time and their causes. It is an example for the general issue that undersampling of ocean phenomena in time and space limits our current ability to assess present states, to distinguish effects of anthropogenic change from natural variability, and to project future changes (Henson et al., 2010; Beaulieu et al., 2013; Box CC-PP).

6.1.2.2. Paleontological Records

Paleontological records in marine sediments provide long-term, low-resolution data on the spatial distributions of organisms and their abundances from all ages and latitudes. This information can be readily related to the concurrent shifts in multiple environmental properties that are also recorded in these sediments. The records provide insights into shifts, expansions, and contractions of biogeographic ranges; species extinctions and emergences; and changes in species abundance, as well as the environmental forcings to which organisms respond. Temporal trends reveal influences of temperature, hypoxia, CO_2, and food availability on organisms and ecosystems (Section 6.1.1; Figure 6-3).

Owing to insufficient resolution, the geological record often does not allow the direct attribution of a biological change to a single driver or the identification of various drivers and their relative importance. Support for projections of future changes in present-day ecosystems and their services is thus limited (*low confidence*; Sections 6.4, 6.5). Nonetheless, information gained from the geological record is invaluable, as both paleo and present climatic shifts share the same combination and sign of environmental changes: increasing atmospheric CO_2 causing warming and CO_2 enrichment in the surface ocean, leading to enhanced stratification of the upper ocean and a decrease in dissolved O_2 (WGI AR5 Chapter 3; Section 5.3). A combination of models (WGI AR5 Chapters 3, 6, 12) and geological data can be used to forecast future impacts on ocean biota (*medium confidence*).

The last glacial-interglacial transition is associated with an average increase in atmospheric CO_2 of approximately 1 µatm per century between 18 and 10 thousand years before present (kyr BP) (WGI AR5 Chapter 5), a significantly slower increase than the approximately 90 µatm in the last century (WGI AR5 Chapters 5, 6). Consequently, the average pH change of 0.002 pH units per century during the glacial-interglacial transition is small relative to the ongoing anthropogenic perturbation of >0.1 pH unit per century (WGI AR5 Section 3.8.2). Overall the upper glacial ocean was more O_2-rich than today's ocean (Jaccard and Galbraith, 2012) and between 0.7°C and 2.7°C colder, with strong regional differences of up to 10°C cooling in the North Atlantic and 2 to 6°C in the Southern Ocean (WGI AR5 Chapter 5, Table 5.2). During warming from the glacial into the interglacial marine plankton such as foraminifera, coccolithophores, diatoms, dinoflagellates, and radiolarians showed marked poleward range expansion (*high confidence*; see WGI AR5 Section 5.7; CLIMAP Project Members, 1976; MARGO Project Members, 2009). Under the lower glacial CO_2 concentrations, calcification in planktonic foraminifera was higher (*limited evidence*, *medium agreement*).

The most prominent abrupt climate change periods in the recent geological record, developing within 10 to 100 years, are associated with Dansgaard-Oeschger (DO) and Heinrich events (WGI AR5 Section 5.7), which occurred repetitively during the last 120 kyr. Whereas the atmospheric changes happened within a few decades, the sea surface temperature in the North Atlantic changed by up to 5°C within decades to centuries (WGI AR5 Section 5.7). Southern Ocean temperature changes were slower (hundreds to thousands of years; Barker et al., 2009). The cold phase of a DO event led to the migration of polar foraminiferal species toward the equator, in the North Atlantic as far south as the Iberian Peninsula (Martrat et al., 2004). Abrupt (approximately 100-year) abundance changes in the Southern Ocean were associated with latitudinal shifts in the Antarctic Circumpolar Current and associated species (Barker et al., 2009) akin to modern changes in plankton range due to warming (Box CC-MB, Box 6-1). During the DO warm phases the Monsoon-driven Arabian Sea upwelling records show enhanced primary

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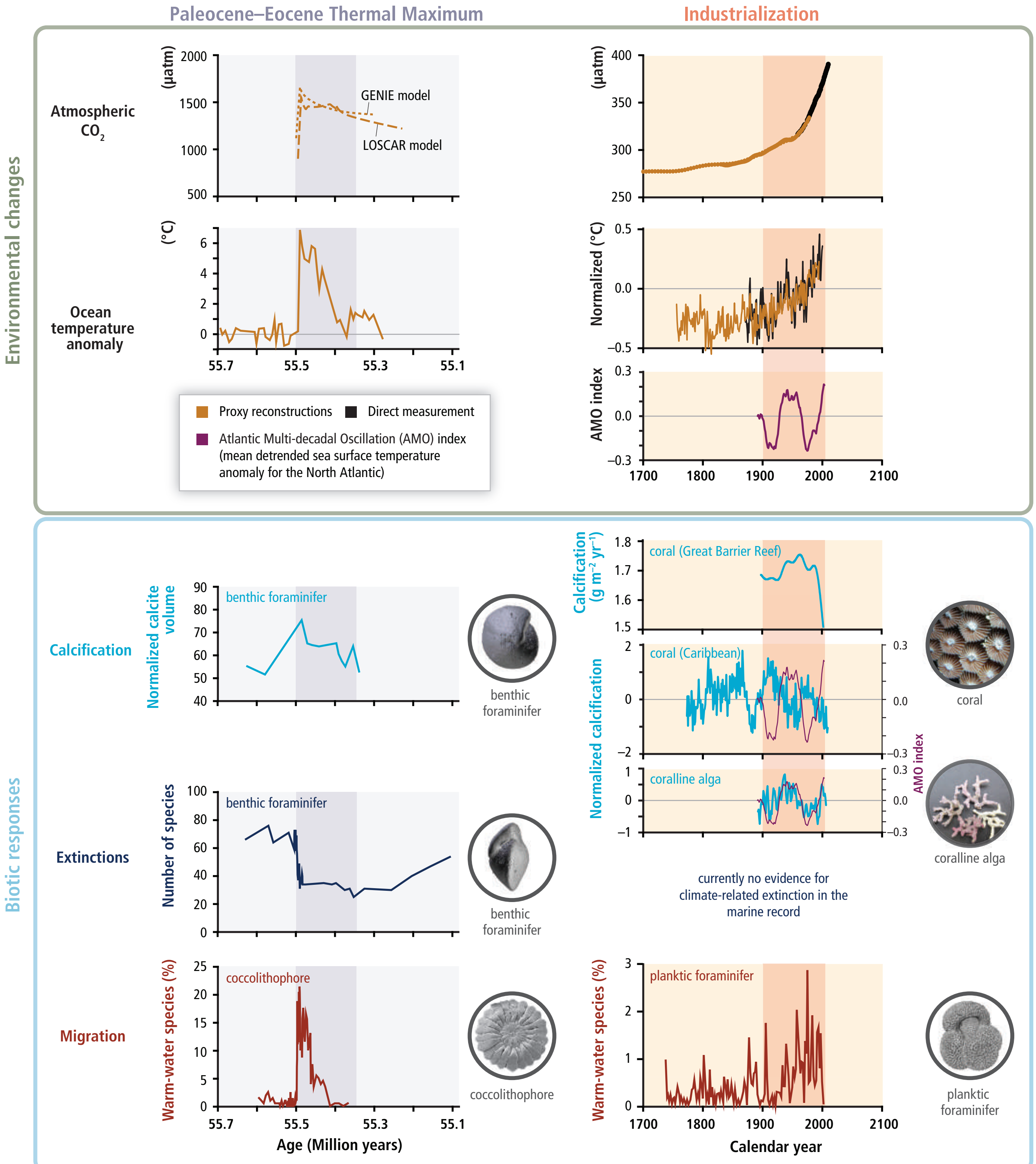


Figure 6-3 | Environmental changes (top) and associated biological responses (bottom) for the Paleocene–Eocene Thermal Maximum (PETM, left) and the industrial era (right). The PETM represents the best geological analog for the future ocean because of its rapid environmental change. Episodes of largest environmental change are indicated with darker bands. Note the different time scale between the two columns. Both time intervals are characterized by rapid warming both on land and in the ocean (modern: Wilson et al., 2006 and PETM: Kennett and Stott, 1991) and increases in CO_2 (modern: Etheridge et al. 1996; Keeling et al., 2005 and PETM: Zeebe et al., 2009 (LOSCAR model); Ridgwell and Schmidt, 2010 (Grid Enabled Integrated Earth System Model (GENIE model))). For the recent industrial era, the Atlantic Multi-decadal Oscillation (AMO; see Figure 6-1 and Section 6.1.2.1) is shown to highlight an example of high-frequency sea surface temperature fluctuations (Enfield et al., 2001) and their influence on marine biota. Note the species-specific calcification responses to climate change with decreases, increases, and high variability (coralline alga: Halfar et al., 2011; coral: Vásquez-Bedoya et al., 2012; De'ath et al., 2013; PETM: Foster et al., 2013). While there was extinction during the PETM (Thomas, 2003), there is currently no evidence for climate-related extinction in the marine record. Warming led to migration of warm-water species into previous cold-water habitats (modern: Field et al., 2006; PETM: Bralower, 2002). Pictures are examples of organisms highlighting the processes in each panel, and are not to scale.

and export production, reduced oxygenation, and denitrification, all within approximately 200 years (Higginson et al., 2004).

The last time the atmospheric CO_2 content approached that of today was during the Pliocene warm period (3.3 to 3.0 million years ago (Ma)), with long periods of atmospheric CO_2 levels between 330 and 400 µatm (Pagani et al., 2010; Seki et al., 2010) and equilibrated temperatures approximately 2°C warmer than today (*medium confidence*; Haywood et al., 2009; WGI AR5 Chapter 5). The Mid-Pliocene Warm Period saw a poleward expansion of tropical planktonic foraminifera (*high confidence*; Dowsett, 2007). Coccolithophores (Bown et al., 2004), corals (Jackson and Johnson, 2000), and mollusks (Vermeij and Petuch, 1986) remained unaffected with respect to rates of species extinction or emergences compared to background rates.

Perhaps the best analog for the future ocean is the Paleocene-Eocene Thermal Maximum (PETM, 55.3 Ma). The PETM was an event of warming (Dunkley Jones et al., 2013), and ocean acidification (Zachos et al., 2005) over millennia (Cui et al., 2011; Stassen et al., 2012) with increased runoff and nutrients into the shelf ecosystems. Model simulations for the PETM show 10 times lower rates of CO_2 input and hence ocean acidification compared to today (*medium confidence*; Ridgwell and Schmidt, 2010). Depending on the assumed rate and magnitude of the CO_2 release, models project pH declined by 0.25 to 0.45 units in PETM surface waters and a reduction in surface ocean aragonite saturation from $\Omega = 3$ to $\Omega = 2$ or even as low as 1.5 (Ridgwell and Schmidt, 2010). Warming caused range expansions of warm-water taxa toward higher latitudes (*high confidence*). The composition of plankton assemblages changed both within and between phytoplankton groups (Gibbs et al., 2006; Sluijs and Brinkhuis, 2009), possibly reflecting the warming trend and/or changes in nutrient availability (Sections 6.2.2-3). There was no bias in extinction toward more heavily calcifying species, possibly as slow CO_2 input led to minor surface water acidification. By contrast, benthic foraminifera, the dominant deep water eukaryote, recorded up to 50% extinction (Thomas, 2007). In contrast to sediment dwellers, more mobile pelagic crustaceans (ostracods) did not show any significant change in species composition (Webb et al., 2009). In shallow coastal waters, calcareous algae and corals were replaced by symbiont-bearing benthic foraminifera (*medium confidence*; Scheibner and Speijer, 2008).

The warm climates of the Mesozoic (251 to 65 Ma) led to a number of anoxic events in the oceans (Jenkyns, 2010). In some cases, OMZs expanded vertically, leading to anoxia in upper water layers (Pancost et al., 2004). Some of the Cretaceous oceanic anoxic events were associated with extinctions or increased species turnover (normalized sum of originations and extinctions) of planktonic foraminifera and radiolarians (30%). Such turnover was very small in other groups of organisms (e.g., a maximum of 7% of coccolithophores; Leckie et al., 2002). The attribution of these evolutionary changes to reduced O_2 is tenuous as warming, changes in nutrient supply, and possibly ocean acidification occurred concomitantly (Hönisch et al., 2012).

Global-scale collapse of marine ecosystems is rare, even in the geological record. Some mass extinctions, in particular the Permian Period extinction 251 Ma, have been associated with large-scale inputs of carbon into the atmosphere and ocean, with associated warming and deep-sea O_2 decline (Knoll et al., 2007; Kiessling and Simpson, 2011). The end-Permian mass extinction preferentially affected reef organisms such as corals and sponges resulting in a 4 Myr period without reef builders (Kiessling and Simpson, 2011), and underscores that vulnerabilities differ among organisms depending on anatomy, physiology, and ecology (Knoll and Fischer, 2011). The rates of environmental change and any potential acidification have not yet been accurately constrained for these events.

Of the last 100 Myr, only the last 2 Myr had CO_2 levels of approximately 190 to 280 ppm, comparable to preindustrial values. Values like those predicted for the mid and end of this century can solely be found in the geological record older than 33 Ma, with large uncertainties in the absolute numbers (WGI AR5 Section 5.3; Hönisch et al., 2012). That marine biota thrived throughout high CO_2 times cannot imply that marine organisms will remain unaffected in a future warm, high-CO_2 world. The key environmental issue of the 21st century is one of an unprecedented rate of change, not simply magnitude, of CO_2 levels (Hönisch et al., 2012). The current rate and magnitude of ocean acidification are at least 10 times faster than any event within the last 65 Ma (*high confidence*; Ridgwell and Schmidt, 2010) or even 300 Ma of Earth history (*medium confidence*; Hönisch et al., 2012). The slower events in geological history provide *robust evidence* (*high agreement*) for environmentally mediated changes in biogeographic ranges of fauna and flora, their compositional changes, extinctions, and, to much lesser degree, emergences (*very high confidence*). No past climate change event perfectly parallels future projections of anthropogenic climate change, which is unprecedented in evolutionary history. Existing similarities indicate, however, that future challenges (Sections 6.1.1, 6.3.1-8) may be outside the adaptive capacity of many organisms living in today's oceans (*low* to *medium confidence*).

6.2. Diversity of Ocean Ecosystems and Their Sensitivities to Climate Change

Global-scale observation and modeling studies provide *robust evidence* of present and future climate-mediated alterations of the ocean environment (*high agreement*; Section 6.1.1; WGI AR5 Chapters 3, 6; Bopp et al., 2013), which in turn impact ocean ecosystems (*high confidence*; Boyd and Doney, 2002; Drinkwater et al., 2010; Hoegh-Guldberg and Bruno, 2010). An assessment of present findings and projections requires knowledge of the characteristics of ocean biota and ecosystems and their climate sensitivity.

Life on Earth is diverse as a result of nearly 4 billion years of evolutionary history. Marine microorganisms are the oldest forms of life and the most functionally diverse; multicellular organisms are constrained to limited functional abilities. Knowledge of overarching similarities across the organism domains Archaea, Bacteria, and Eukarya (Woese et al., 1990) or kingdoms Bacteria, Protozoa, Fungi, Plantae, Animalia, and Chromista (Cavalier-Smith, 2004) would facilitate projections of climate impacts. The phylogenetic and metabolic diversity of microbes (i.e., viruses, archaea, bacteria, protists, and microalgae) sustains key ecosystem processes such as primary production, CO_2 fixation and O_2 production, the conversion of nitrogen into ammonia (N_2 fixation), and the use of nitrate, sulfate, CO_2, and metals (iron and manganese) in metabolism instead of O_2 when it is absent. Microbes enhance the horizontal transfer of genetic information between unrelated individuals, thereby enhancing biodiversity (McDaniel et al., 2010). Microbes may respond to climate change by exploiting their large diversity, undergoing species replacements (Karl et al., 2001), and thereby sustain their biogeochemical roles. Species replacements also occur among plants and animals, but in most cases research has focused on their resilience, well-being, abundance, survival, and conservation under climate change (FAQ 6.2).

6.2.1. Pelagic Biomes and Ecosystems

Pelagic organisms are key to biogeochemical processes in the ocean. The base of the marine food web is the photosynthetic fixation of CO_2 by phytoplankton, a process termed (net) primary production (NPP; Box CC-PP). Photosynthesis is controlled by light, temperature, inorganic nutrients (CO_2, nitrate, phosphate, silicate, and trace elements including iron), and the density-dependent stability of the surface mixed-layer depth (MLD) (Section 6.1.1; Figure 6-2; Sverdrup, 1953; González-Taboada and Anadón, 2012). Environmental variability and the displacement of organisms by ocean currents cause variability in phytoplankton productivity, competitiveness, and natural selection (Margalef, 1978) and result in changes in carbon sequestration (Box CC-PP; Figure 6-4). Nutrient limitation leads to a decrease in NPP or chlorophyll levels and a reduction in the amount of energy supplied to higher trophic levels, including fish and invertebrates (*high confidence*; Ware and Thomson, 2005; Brander, 2007), affecting fishery yields (Cheung et al., 2008; Friedland et al., 2012). The wide range of trophic structures in marine food webs and the potentially nonlinear changes in energy transfer under different NPP and temperature scenarios (Stock and Dunne, 2010) hamper accurate projections of changes in higher trophic levels.

6.2.2. Benthic Habitats and Ecosystems

The ocean's primary production is inextricably linked with benthic (sea floor) communities via the biological pump (Figure 6-4), the chemical exchange of nutrients and gases, and the existence of organisms with both pelagic and benthic life history stages. Even in abyssal habitats, a continuous rain of organic detritus serves as the primary source of carbon and energy. Therefore climate impacts on surface marine ecosystems will impact even the deepest benthic communities, even if direct changes to their physical habitat do not occur (Smith et al., 2009).

Benthic organisms living in shallow waters or the intertidal zone (where they encounter temporary exposure to air) are exposed to widely fluctuating and progressively changing means and extremes of environmental variables, such as temperature, oxygen, CO_2, salinity, and sea level (WGI AR5 Chapters 3, 13; Sections 6.3.1-3, 6.3.5). Plants and sessile or slow moving animals may be unable to escape from unfavorable changes except by means of advection of fertilized eggs or planktonic larvae. If climate change harms those species engineering benthic habitats, the entire ecosystem may be impacted. This concerns those ecosystem engineers, which form habitat from the structures they produce (e.g., corals forming skeletons; Section 6.3.1) and those forming habitat through their behavior (e.g., worms reworking and irrigating sediment in a process termed bioturbation). Effects on both types of ecosystem engineers (Sections 6.3.1-8) influence the regeneration of nutrients and affect benthic-pelagic coupling.

6.3. Climate Change Impacts from Organism to Ecosystem

Understanding climate-induced alterations in the functioning of individual organisms, species populations, communities (assemblages of various species), and ecosystems builds on studies in the laboratory, in micro- and mesocosms (closed small- to medium-sized experimental systems approximating natural conditions, holding selected biological communities), and of biota or communities in the field as well as modeling. These data inform us which taxonomic groups in what regions are more susceptible to climate change (Boyd et al., 2011). Empirical studies of marine organism and ecosystem sensitivities have begun identifying the mechanisms and processes linking climate to ecosystem changes (Drinkwater et al., 2010; Ottersen et al., 2010). Changes in ecological community composition, species interactions, and food web dynamics often build on organismal effects elicited by climate forcing (e.g., Section 6.3.1.5; Boyd et al., 2010; Ottersen et al., 2010). The underlying mechanisms respond to climate-related factors in a hierarchy from organism (highest), tissue, cell to molecular (lowest)

Table 6-1 | To assess how a changing climate will alter the ocean's biological pump (Figure 6-4) and determine the resulting biogeochemical feedbacks on global climate, changes in a wide range of processes from cells to ocean basins, and from epipelagic to mesopelagic, must be quantified. This table illustrates the complexity of the integrated knowledge platform needed to provide evidence of these biogeochemical ramifications and thus the present limits to clear conclusions about climate-induced effects on the biological pump (NPP = net primary production; C = carbon; TEP = transparent exopolymer particle; DOM = dissolved organic matter; POM = particulate organic matter).

Alteration of physiological rates	Biogeographical changes/ community shifts	Altered foodweb structure: trophodynamics	Changes to particle dynamics	Biogeochemical changes/ climatic feedbacks
• NPP (Bopp et al., 2002, 2013) • Particle solubilization through bacterial ectoenzymes (Christian and Karl, 1995) • TEP production (Engel et al., 2004) • Microzooplankton grazing rates (Rose et al., 2009)	• Microbial community structure (Giovannoni and Vergin, 2012) • Phytoplankton community structure, e.g., biomes (Boyd and Doney, 2002) • Alteration of zooplankton biomes (Beaugrand et al., 2009) • Faunistic shifts at depth (Jackson and Burd, 2001)	• Altered prey-predator linkages (Lewandowska and Sommer, 2010)	• Faecal pellet geometry (Wilson et al., 2008) • C partitioning between DOM vs. POM, e.g., TEP (Riebesell et al., 2007) • Sinking rates/seawater viscosity (Lam and Bishop, 2008) • Ballasting, e.g., calcite versus opal (Klaas and Archer, 2002)	• Particle flux/C sequestration (Bopp et al., 2002) • Shifts in elemental stoichiometry of planktonic communities (Karl et al., 2003) • Remineralization rate; [O_2], hypoxia; nutrient resupply (Gruber, 2011) • Activity of the microbial loop; vertical carbon export (Grossart et al., 2006; Piontek et al., 2010)

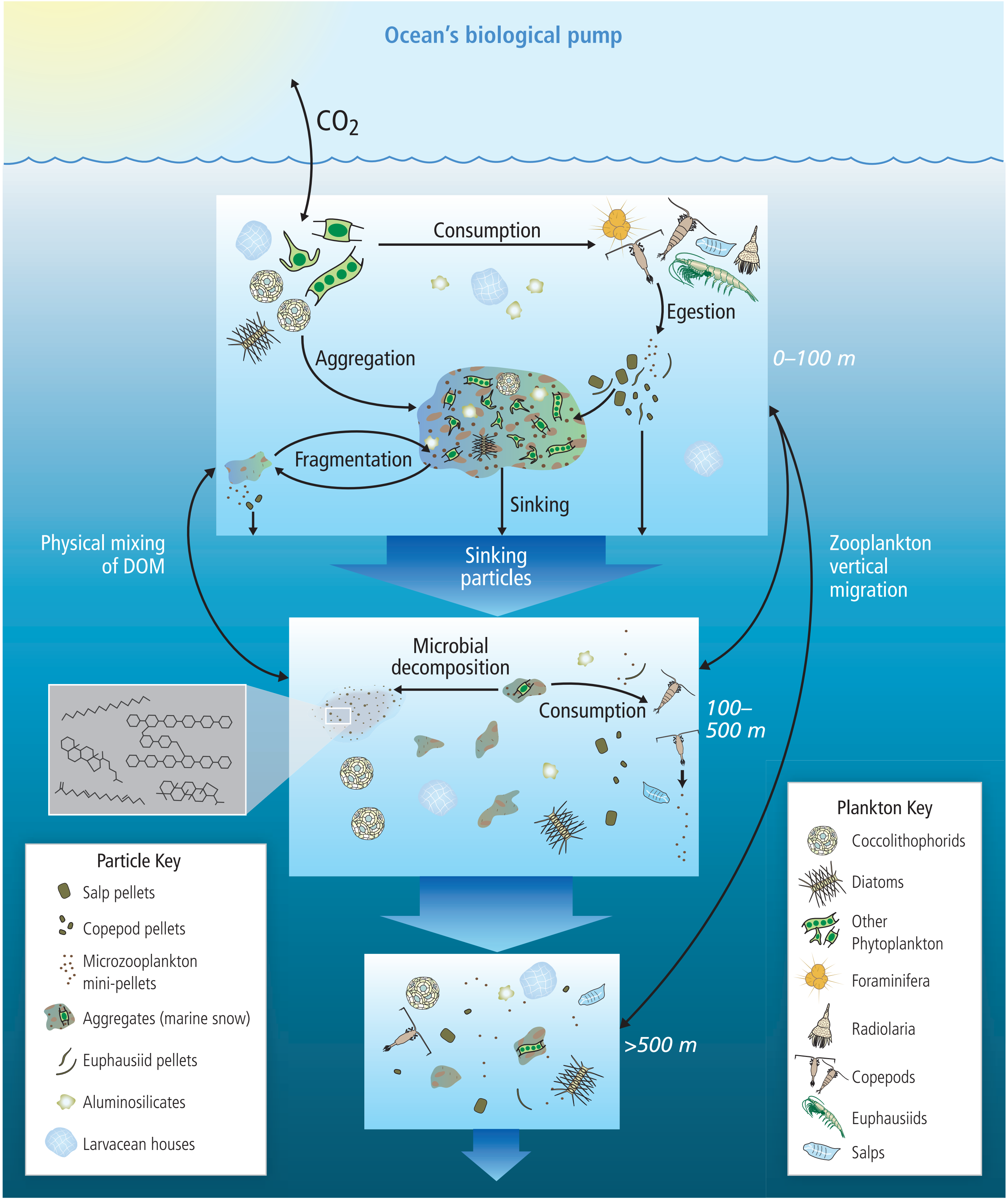


Figure 6-4 | A schematic representation of the ocean's biological pump, which will be influenced by climate change and is a conduit for carbon sequestration. It is difficult to project how the pump might be altered and whether it would represent a positive or negative feedback to climate change through the cumulative effects of affected processes, surface to depth (Table 6-1): shifts in net primary production, floristic and faunistic community composition in the pelagic realm, and in grazing rates; alterations to the ballasting of settling particles and the proportion of net primary production released as dissolved organic matter; modified bacterial enzymatic rates and particle solubilization; faunistic shifts at depth. Note that the relative sizes of the organisms, particles, and particle building blocks are not presented to scale (modified from Buesseler et al. (2008) by J. Cook / WHOI).

Frequently Asked Questions

FAQ 6.2 | What is different about the effects of climate change on the oceans compared to the land, and can we predict the consequences?

The ocean environment is unique in many ways. It offers large-scale aquatic habitats, diverse bottom topography, and a rich diversity of species and ecosystems in water in various climate zones that are found nowhere else.

One of the major differences in terms of the effect of climate change on the oceans compared to land is ocean acidification. Anthropogenic CO_2 enters the ocean and chemical reactions turn some of it to carbonic acid, which acidifies the water. This mirrors what is also happening inside organisms once they take up the additional CO_2. Marine species that are dependent on calcium carbonate ($CaCO_3$), such as shellfish, seastars, and corals, may find it difficult to build their shells and skeletons under ocean acidification. In general, animals living and breathing in water like fish, squid, and mussels have between five and 20 times less CO_2 in their blood than terrestrial animals, so CO_2-enriched water will affect them in different and potentially more dramatic ways than species that breathe in air.

Consider also the unique impacts of climate change on ocean dynamics. The ocean has layers of warmer and colder water, saltier or less saline water, and hence less or more dense water. Warming of the ocean and the addition of more freshwater at the surface through ice melt and higher precipitation increases the formation of more stable layers stratified by density, which leads to less mixing of the deeper, denser, and colder nutrient-rich layers with the less dense nutrient-limited layers near the surface. With less mixing, respiration by organisms in the mid-water layers of stratified oceans will produce oxygen-poor waters, so-called oxygen minimum zones (OMZs). Large, more active fish can't live in these oxygen poor waters, while more simple specialized organisms with a lower need for oxygen will remain, and even thrive in the absence of predation from larger species. Therefore, the community of species living in hypoxic areas will shift.

State-of-the-art ecosystem models build on empirical observations of past climate changes and enable development of estimates of how ocean life may react in the future. One such projection is a large shift in the distribution of commercially important fish species to higher latitudes and reduced harvesting potential in their original areas. But producing detailed projections, for example, what species and how far they will shift, is challenging because of the number and complexity of interactive feedbacks that are involved. At the moment, the uncertainties in modeling and complexities of the ocean system even prevent any quantification of how much of the present changes in the oceans are being caused by anthropogenic climate change or natural climate variability, and how much by other human activities such as fishing, pollution, etc.

It is known, however, that the resilience of marine ecosystems to adjust to climate change impacts is *likely* to be reduced by both the range of factors and their rate of change. The current rate of environmental change is much faster than most climate changes in the Earth's history, so predictions from longer term geological records may not be applicable if the changes occur within a few generations of a species. A species that had more time to adapt in the past may simply not have time to adapt under future climate change.

levels of biological organization (Pörtner, 2002a; Pörtner and Knust, 2007; Raven et al., 2012). Such knowledge aids the interpretation and attribution to climate change of observed effects and is a major asset for projections of future impacts.

The genetic and physiological underpinning of climate sensitivity of organisms sets the boundaries for ecosystem response and provides crucial information on sensitivities, resilience, and the direction and scope of future change. As anthropogenic climate change accelerates, a key issue is whether and how quickly organisms can compensate for effects of individual or multiple drivers, by short-term acclimatization or long-term evolutionary adaptation across generations. Evolutionary adaptation depends on the genetic variation within a population, from which the environment selects the fittest genotypes (Rando and Verstrepen, 2007; Reusch and Wood, 2007). Genetic variation depends on mutation rates, generation time, and population size (Bowler et al., 2010). However, epigenetic mechanisms, such as modifications of the genome by DNA methylation, can also influence fitness and adaptation (Richards, 2006) and can be remarkably rapid as seen in terrestrial ecosystems (Bossdorf et al., 2008). In plants and animals the rate of evolutionary adaptation is constrained by long generation times, but enhanced by high phenotypic variability and high mortality rates among early life stages as a selection pool (e.g., Sunday et al., 2011). The limits to acclimatization or adaptation capacity are presently unknown.

However, mass extinctions occurring during much slower rates of climate change in Earth history (Section 6.1.2) suggest that evolutionary rates in some organisms may not be fast enough to cope.

Comprehensive understanding of climate change effects on ecosystems requires addressing the effects of individual drivers across organism taxa (Sections 6.3.1-4), the integrated action of multiple drivers (Section 6.3.5), the consequences for food webs (Section 6.3.6), and the specific effects on animals breathing in air (Section 6.3.7) and operating at the highest trophic levels.

6.3.1. Temperature Effects

The effects of temperature on ecosystems largely result from organismal responses. This requires that information on organisms' thermal sensitivities, limits, and functional properties is used to assess how temperature changes have affected and will continue to affect species distributions, abundances, diversity, trophic interactions, community assemblages, risks of species extinctions, and ecosystem functioning. Organisms also respond to temperature-driven changes in the physical environment such as stratification, reduced sea ice cover, and freshening. Ambient temperature interacts with other drivers such as ocean acidification and hypoxia (Section 6.3.5). Ambient temperature plays a more limited role for marine mammals and seabirds (Section 6.3.7).

6.3.1.1. Principles

All organisms including marine ones have limited temperature ranges within which they live and function. Organismal performance is related to temperature by curves called thermal reaction norms (Figure 6-5), which *likely* apply across all organisms (Chevin et al., 2010), from viruses (Knies et al., 2006), bacteria (Ratkowsky et al., 1983), and phytoplankton (Eppley, 1972; Thomas et al., 2012) to macroalgae and plants (Bolton and Lüning, 1982; Müller et al., 2009; Vitasse et al., 2010) and animals (Huey and Kingsolver, 1989; Angilletta, 2009). Heat tolerance thresholds differ greatly between organisms and are hypothesized to be lowered by rising organizational complexity and body size (Pörtner, 2002a,b). Maximum heat limits of animals and plants are close to the maximum

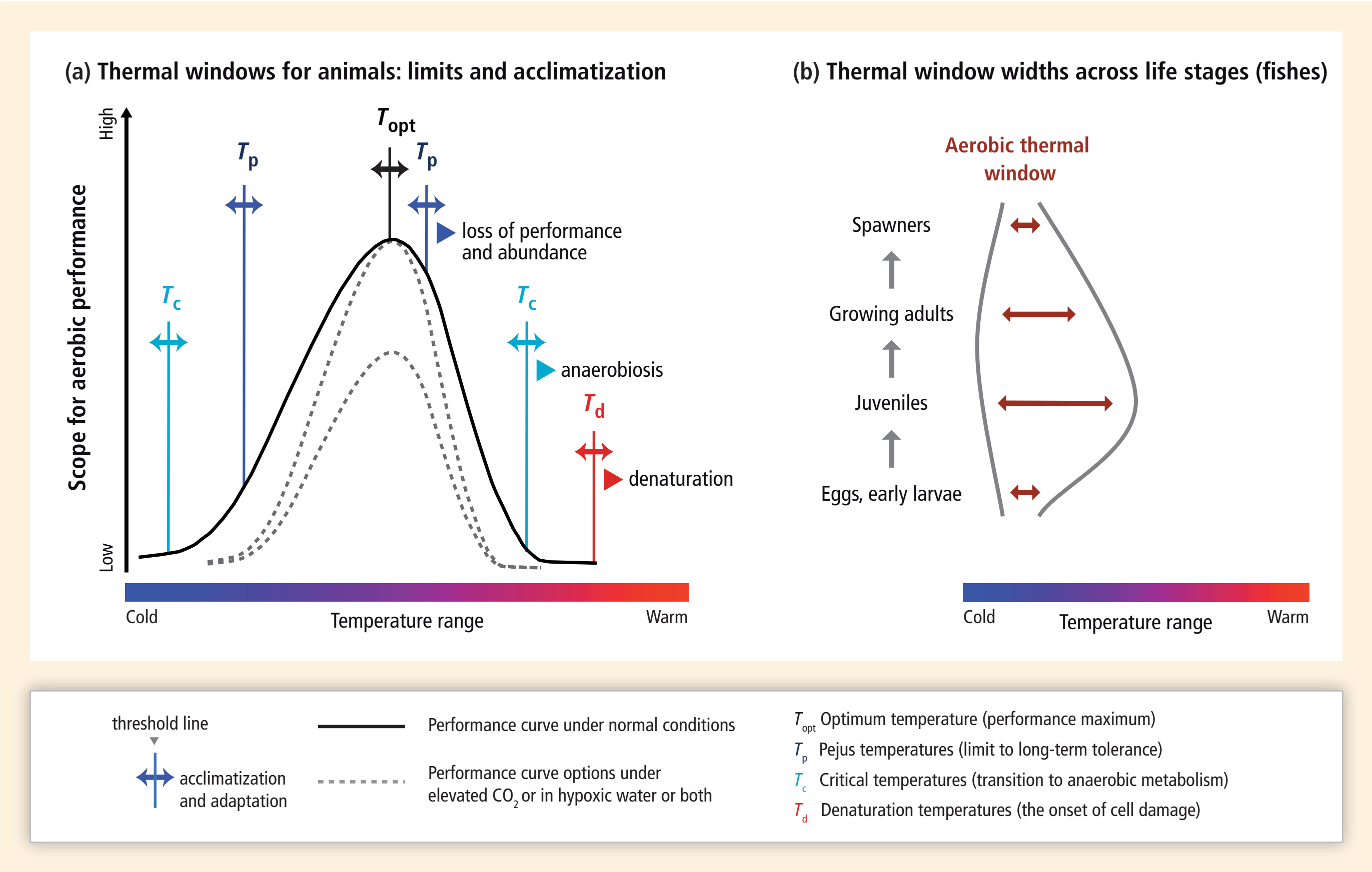


Figure 6-5 | Thermal specialization of an organism explains the why, how, when, and where of climate sensitivity. (a) The thermal tolerance range and performance levels of an organism are described by its performance curve (exemplified for an animal). Each performance (e.g., exercise, growth, reproduction) is maximal at its optimum temperature (T_{opt}), and becomes progressively constrained during cooling or warming. Surpassing the first low- and high-temperature thresholds (T_p; p, pejus: getting worse) means going into time-limited tolerance. Once further cooling or warming surpasses the next low or high thresholds (T_c; c, critical), oxygen availability becomes insufficient and an anaerobic metabolism begins. Denaturation temperatures (T_d) are even more extreme and characterized by the onset of damage to cells and proteins. Horizontal arrows indicate that T_p, T_c, and T_d thresholds of an individual can shift, within limits, between summer and winter (seasonal acclimatization) or when the species adapts to a cooler or warmer climate over generations (evolutionary adaptation). Under elevated CO_2 levels (ocean acidification) and in hypoxic waters performance levels can decrease and thermal windows narrow (dashed gray curves). (b) The width of the thermal range (horizontal arrows) also changes over time when an individual develops from egg to larva to adult and gains weight and size. Blue to red color gradients illustrate the range between cold and warm temperatures (after Pörtner, 2002a, 2012; Pörtner and Farrell, 2008).

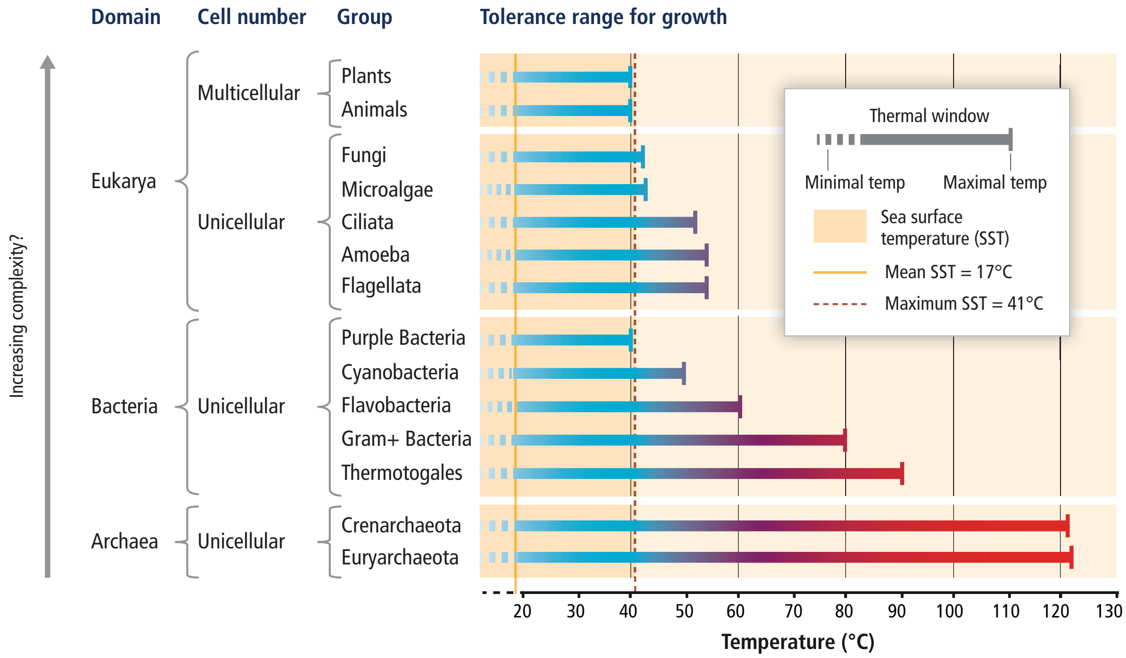


Figure 6-6 | Maximal values of temperature covered by various domains and groups of free-living marine organisms (bacteria to animals; domains and groups modified after Woese et al., 1990). High organizational complexity is hypothesized to be associated with decreasing tolerance to heat and to enable an increase in body size which in turn, decreases heat tolerance further (Sorokin and Kraus, 1962; Chevaldonné et al., 2000; Alker et al., 2001; Baumgartner et al., 2002; Pörtner, 2002a,b; Campbell et al., 2006; De Jonckheere et al., 2009, 2011). In the domain Bacteria, the Thermotogales are less complex and most tolerant to high temperatures (Huber et al., 1986; Tenreiro et al., 1997; Takai et al., 1999; Ventura et al., 2000; Abed et al., 2002). The highest temperature at which growth can occur is 122°C for hydrothermal vent archaea, seen under elevated hydrostatic pressure in laboratory experiments (Kashefi and Lovley, 2003; Takai et al., 2008).

temperature found in the warmest oceans (Figure 6-6). Knowledge of reaction norms, thermal limits, and underlying mechanisms is most advanced in animals (Pörtner et al., 2012; see also Section 6.3.1.4). Their role in underpinning biogeography has not been explored systematically in other organisms (e.g., Green et al., 2008), reducing the confidence level in assessments of thermal impacts. In animals, changes in physiological performances influence growth, body size, behavior, immune defense, feeding, reproductive success, biogeography, phenology, and therefore ecosystem structure and functioning. Shape and width of the curves can shift through acclimatization and evolutionary adaptation (Figure 6-5a) and during life history (Figure 6-5b), with implications for the distribution boundaries of species or populations (Section 6.3.1.5).

For any species, tracking the climate-induced displacement of tolerated ambient temperatures by undergoing shifts in biogeographical ranges to, e.g., higher latitudes during warming (Section 6.3.1.5; Figure 6-7) can be understood as a simple mode of adaptation, implemented through dispersal (e.g., of pelagic life stages), active movements (e.g., of migrating adult fishes), or passive displacement (e.g., of early life stages or plankton with drifting water masses). Conversely, fully completed acclimatization or evolutionary adaptation (Figure 6-5) would involve shifting thermal tolerance ranges and allow species to resist the temperature trend (e.g., warming) and to sustain fitness in their previous habitat.

6.3.1.2. Microbes

Temperature effects on growth, abundance, distribution, phenology, and community structure of highly diverse microbes have large implications for ecosystem functioning (Section 6.3; Box CC-PP). A warming ocean may initially enhance the metabolic rates of microbes (Banse, 1991) and stimulate their overall growth (Bissinger et al., 2008). Data from the Continuous Plankton Recorder (Section 6.1.2) in the Northeast Atlantic confirm that warming from 1960 to 1995 enhanced phytoplankton growth (Edwards et al., 2001). Eventually, with warming, the thermal tolerance of some groups will be challenged (Chevin et al., 2010), leading to the replacement of species. This is reflected in increasing fractions of smaller phytoplankton in warmer relative to colder waters (Morán et al., 2010; Flombaum et al., 2013).

In response to transient warming, phytoplankton distribution in the North Atlantic shifted poleward by hundreds of kilometers per decade since the 1950s. Phenology of plankton in the North Atlantic was also affected, with differences in sensitivity between groups (*high confidence*; Section 6.3.1.5; Box 6-1). Coccolithophore blooms (*Emiliania huxleyi*) in the Bering Sea were reported for the first time during the period 1997–2000, probably in response to a 4°C warming, combined with a shallower mixed layer depth, higher light levels and low zooplankton grazing (Merico et al., 2004). Loss of multi-year Arctic sea ice has had a profound effect on the diversity, structure, and function of the epipelagic microbial assemblage (i.e., found in the layer into which enough light penetrates for photosynthesis) (Comeau et al., 2011), and further warming is likely to have even greater impacts on the food web and on ecosystem services (*medium confidence*). Warming may also have caused the southward range extension of coccolithophores in the Southern Ocean in the 2000s (Cubillos et al., 2007). However, further experimental and field observations (Giovannoni and Vergin, 2012) are required to validate model projections (Taucher and Oschlies, 2011) of differential responses to warming by different microorganisms.

6.3.1.3. Macroalgae and Seagrasses

Macrophytes in coastal waters (Chapter 5) cover 0.6% of the world's marine areas and supply about 2 to 5% of total oceanic production (Smith, 1981; Charpy-Roubaud and Sournia, 1990; Field et al., 1998). They have limited temperature ranges and are sensitive to temperature extremes (*high confidence*), resulting in changes of photosynthesis, growth, reproduction, and survival (following the principles of Figures 6-5, 6-6; and Harley et al., 2012), with consequences for their abundance, distribution, and productivity. Ice retreat in polar areas leads to an expansion of macroalgal distribution, for example, in the Antarctic (Quartino et al., 2013).

Warm- versus cold-water-adapted species may have different sensitivities to warming and show a range of responses in distribution shifts (Lima et al., 2007). Temperate macroalgae with wide windows of thermal tolerance acclimatize by shifting these windows following seasonal temperature changes (Kübler and Davison, 1995). Antarctic and tropical macroalgae are exposed to permanently low or high temperatures, respectively, and have consequently specialized in a limited temperature range, paralleled by a low acclimatization potential (Pakker et al., 1995; Eggert et al., 2006; Gómez et al., 2011). Thus, Antarctic and tropical macroalgae appear to be most vulnerable to warming (*high confidence*; Short and Neckles, 1999). While observations in the tropics indicate that seagrasses tolerate higher temperatures than seaweeds (Campbell et al., 2006), an increase in maximum temperature by >1°C from 1988–1999 to 2002–2006 (Section 30.5.3.1.5) led to increased seagrass shoot mortality in the Mediterranean Sea (Marbà and Duarte, 2010). The molecular basis of acclimatization and evolutionary adaptation, as well as their limitation in relation to the climate regime, require further study in the macrophytes.

6.3.1.4. Animals

The mechanisms shaping the thermal performance curve and, thereby, an animal's thermal niche have been explained by the concept of "oxygen and capacity limited thermal tolerance" (OCLTT), applicable to marine invertebrates and fishes (Pörtner et al., 2010; see also Figure 6-5a, FAQ 6.2). The temperature range at which animals can function best results from optimal oxygen supply at minimal oxygen usage. At temperature extremes, oxygen supply capacity becomes constrained in relation to demand, and metabolism becomes thermally limited. Beyond upper and lower temperature thresholds (T_p, Figure 6-5a), growth, reproduction, and other key functions decrease. These thresholds change during the individual life cycle, and with body size. At large body size, limitations in oxygen supply are exacerbated and heat tolerance limits shift to lower temperatures.

Surpassing species-specific heat tolerance limits (Figure 6-5, T_p) during warming causes a reduction of abundance (Pörtner and Knust, 2007; Katsikatsou et al., 2012), coral losses (Donner et al., 2005), shifts in the seasonal timing of (zooplankton) biomass formation (Mackas et al., 1998; Schlüter et al., 2010), and changes in growth (Lloret and Rätz, 2000; Brunel and Dickey-Collas, 2010). During early life, owing to incomplete development, or as adult spawners, owing to large body size, animals may become more sensitive to warming because of narrower thermal windows (Pörtner et al., 2008). This may cause high vulnerability of winter-spawning Atlantic cod to warming winter to spring temperatures (Table 6-2). In contrast, adult bigeye, bluefin, and skipjack tuna spawn at high temperatures. They need to prevent overheating by moving to cooler (deeper) waters (Lehodey et al., 2011).

Although temperature means are still most commonly used when attributing responses of marine organisms to climate effects, temperature extremes rather than means are most often mediators of effects (e.g., Easterling et al., 2000; Wethey et al., 2011; Wernberg et al., 2013; Figure 6-5). During heat exposure near the borders of the distribution range (including the high intertidal or warming surface waters), reductions in growth, activity, and abundance accompany even small (<0.5°C) shifts in ambient temperature extremes (e.g., Takasuka and Aoki, 2006; Pörtner and Knust, 2007; Nilsson et al., 2009; Neuheimer et al., 2011). Local extinction events follow as a result of mortality or behavioral avoidance of unfavorable thermal environments (Breau et al., 2011). Shifted species distribution ranges follow temperature clines from high to low, usually along latitudes, a lateral gradient at basin scale (Perry et al., 2005; Poloczanska et al., 2013), or a vertical temperature gradient to deeper waters (*high confidence*; Dulvy et al., 2008; Section 6.5.3; see also Figure 6-5b, Box CC-MB).

Adopting OCLTT principles has enabled modeling studies to project climate effects (Section 6.5), and paleo-studies to explain climate-induced mass extinction events and evolutionary patterns in Earth history (Pörtner et al., 2005; Knoll et al., 2007). For example, long-term observations show that warming affects the body size of marine fishes (*medium confidence*). Assessing effects of warming on body size may be complicated by effects on the animal's energy budget, the changing availability and body size of prey species, community structure, species interactions, or effects of fishing (Genner et al., 2010; Cheung et al., 2013a). Below the thermal optimum, warming causes growth and weight-at-age of some juvenile or younger fish populations to increase (e.g., Brunel and Dickey-Collas, 2010; Neuheimer and Grønkjær, 2012). However, OCLTT predicts that small individuals are more heat tolerant than large ones, in line with observations of falling animal body sizes in warming oceans (Box 6-1; e.g., Daufresne et al., 2009). This trend is projected to continue into the 21st century (*medium* to *high confidence*; Cheung et al., 2013a).

Thermal windows of fishes and invertebrates roughly match ambient temperature variability (Figure 6-1) according to climate regime and seasonality (Pörtner and Peck, 2010; Sunday et al., 2012). Sub-Arctic, small, or highly mobile species are eurytherms. They function across a wide temperature range, that is, they have wide thermal windows and distribution ranges, at the expense of higher energetic costs and associated lifestyles (Pörtner, 2002a, 2006). Conversely, high polar species are stenotherms, that is, they have narrow thermal windows and low energy demand lifestyles, making them sensitive to temperature change. In a warming world, polar stenotherms will be marginalized, with no possibility to escape to colder regions (*high confidence*). However, extinction of polar species has not yet been reported. As marine fishes and invertebrates in the Southern Hemisphere are

Table 6-2 | Selected examples of species responses and underlying mechanisms to changing temperature, oxygen level and ocean acidification (OA). References are indicated by superscript numbers and in the footnote.

	Phenomenon	Key drivers	Mechanism/Sensitivity
Biogeography	Northward shift in the distribution of North Sea cod (*Gadus morhua*) stocks between 1977 and 2001. [1,2]	Temperature	Bottlenecks of high sensitivity during early life stages as well as adult spawning stage in winter/early spring.
	Shift from sardines (*Sardinops melanostictus*) to anchovies (*Engraulis japonicus*) in the western North Pacific observed between 1993 and 2003. [3,4]	Temperature	Thermal windows of growth and reproductive output are found at higher temperatures for anchovies than sardines, food preferences of the competing species being similar.
	Variable sensitivity of Pacific tuna species to the availability of dissolved O_2. Bigeye tuna routinely reach depths where ambient O_2 content is below 1.5 ml L^{-1} (≈ 60 µmoles kg^{-1}). [5, 6]	Oxygen	Oxygen transport via hemoglobin is adapted to be highly efficient supporting high metabolic rates as needed during feeding in the OMZ.
	Northward movement of species and the conversion of polar into more temperate and temperate into more subtropical system characteristics in the European Large Marine Ecosystems between 1958–2005. [7, 8]	Warming and current advection	Effects are attributed to climate change but may be influenced by nutrient enrichment and overfishing.
Abundance	Increase in abundance of arctic boreal plankton species, notably the copepods *Calanus hyperboreus*, *Calanus glacialis* and the dinoflagellate *Ceratium arcticum* between 1960 and 2000 in the Newfoundland Shelf, Northwest Atlantic. [9,10]	Temperature	Temperature sensitivity of phyto- and zooplankter resulting from cooling due to increased influx of Arctic water.
	A benthic fish species, the eelpout (*Zoarces viviparus*) at its southern distribution limit, the German Wadden Sea, displayed abundance losses during warming periods and rising summer extreme temperatures between 1993 and 2005, with early disappearance of the largest individuals. [11]	Temperature	Temperature extremes exceed organism's thermal windows, with largest individuals being relatively less tolerant to high temperature than smaller individuals.
	Variable sensitivities to OA within and across animal phyla (Figure 6-10b). [12–21]	Anthropogenic OA, sea water acidification by elevated pCO_2 in OMZs, upwelling areas, involving anthropogenic ocean acidification.	Lowered extracellular (blood plasma) pH causing a lowering of the rates of ion exchange and metabolism in muscle or liver (hepatocytes) of vertebrates and invertebrates. High sensitivity at reduced energy turnover in tissues and/or whole organism by reduced ion exchange, use of more energy efficient transport mechanisms, reduced protein synthesis, enhanced nitrogen release from amino acid catabolism and protein degradation, slower growth.
Phenology	Migration time of pink salmon (*Oncorhynchus gorbuscha*) in Alaska is almost two weeks earlier in 2010s relative to 40 years ago. [22]	Warming	Rapid microevolution for earlier migration timing.
	In the waters around the UK, during a period of warming between 1976 and 2005, the seasonal timing of biological events of all major marine taxonomic groups (plant/phytoplankton, invertebrate and vertebrates) advanced, on average, by 0.31 to 0.43 days $year^{-1}$. [23]	Warming	Sensitivity to seasonal temperature changes as a result of specific thermal windows of different organisms.
Body size and growth	Asymptotic body sizes of different populations of Atlantic cod (*Gadus morhua*) and Atlantic Herring (*Clupea harengus*) are negatively related to temperature. [24, 25]	Warming	At large body size, oxygen supply limitations are exacerbated and the organism reaches its long-term heat tolerance limits at lower temperatures, thus limiting the maximum body size that can be reached.

1. Perry et al. (2005); 2. Pörtner et al. (2008); 3. Takasuka et al. (2007); 4. Takasuka et al. (2008); 5. Lehodey et al. (2011); 6. Seibel (2011); 7. Beaugrand et al. (2009); 8. Philippart et al. (2011); 9. Johns et al. (2001);10. Greene and Pershing (2003); 11. Pörtner and Knust (2007); 12. Reipschläger and Pörtner (1996); 13. Pörtner et al. (2000); 14. Vezzoli et al. (2004); 15. Langenbuch and Pörtner (2003); 16. Fernández-Reiriz et al. (2011); 17. Langenbuch and Pörtner (2002);18. Langenbuch et al. (2006); 19. Michaelidis et al. (2005); 20. Pörtner et al. (1998); 21. Stumpp et al. (2012); 22. Kovach et al. (2012); 23. Thackeray et al. (2010); 24. Taylor (1958); 25. Brunel and Dickey-Collas (2010).

adapted to less variable ocean temperatures than those in the Northern Hemisphere (Jones et al., 1999; Figure 6-1), they may generally be more vulnerable to warming extremes than Northern ones. Tropical species (with thermal windows of intermediate width) live close to the highest temperatures tolerated by marine animals (Figure 6-6). Vulnerability is, therefore, highest for polar stenotherms, similar or lower for tropical, and lowest for temperate species (*high confidence*).

Short-term shifts in thermal thresholds of an individual organism may happen over days and weeks, such as during seasonal acclimatization. Long-term shifts occur over many generations during evolutionary adaptation of a population to cooler or warmer climates (Figure 6-5a; Pörtner, 2006; Pörtner et al., 2008; Eliason et al., 2011). Both acclimatization and adaptation involve adjustments in biochemical characters (membranes, enzymes); however, the capacity to shift those boundaries is limited and depends on the species and the prevailing climate regime (Pörtner et al., 2008, 2012). Ocean acidification, hypoxia, food availability, and stress affect those limits (Section 6.3.5; Figure 6-5a).

Local adaptation may reduce climate vulnerability at the species level, by causing functional and genetic differentiation between populations, thereby enabling the species to cover wider temperature ranges and live in heterogeneous environments. Local adaptation on small spatial scales is particularly strong in intertidal organisms (Kelly et al., 2012). On larger scales, the widening biogeographic and roaming ranges of

Northern Hemisphere eurytherms into Arctic waters (Pörtner et al., 2008) are supported by the differentiation into populations with diverse thermal ranges, combined with high acclimatization capacity. By contrast, such capacity is small in high polar, for example, Antarctic species (Peck et al., 2010). Tropical reef fishes undergo rapid warm acclimation across generations (Donelson et al., 2012) but some may approach animal heat limits. The rates, mechanisms, and limits of thermal acclimatization and evolutionary adaptation are poorly understood (*low confidence*).

6.3.1.4.1. Warm- and cold-water coral communities

Tropical corals live in shallow water and differ from most other animals by hosting dinoflagellates (*Symbiodinium* sp.) in their tissues, which provide the host with organic carbon from photosynthesis and with nitrogen and enable the corals to build and sustain carbonate reefs (Box CC-CR). High light, rapid salinity changes, and small increases in temperature can trigger "coral bleaching", the loss of symbionts and tissue color. In case of warming, early steps involve shifts in the photosynthetic processing of light, generating Reactive O_2 Species (ROS) that may in turn damage the symbionts (Hoegh-Guldberg and Smith, 1989; Glynn and D'Croz, 1990; Jones et al., 1998; Hoegh-Guldberg, 1999). Mass bleaching correlates with small temperature anomalies (+1°C to 2°C of the long-term summer maximum, satellite observations), causing mortalities (Goreau and Hayes, 1994; Strong et al., 2011) and decreasing coral abundance, on average by 1 to 2% per year (*high confidence*; Bruno and Selig, 2007; see also Box CC-CR; Section 30.5.6).

The degree of impact will depend on the coral reefs' adaptability to thermal stress and the interaction of multiple drivers (Meissner et al., 2012; Teneva et al., 2012; see also Box CC-CR). Such capacity is suggested by different heat tolerances among coral genera (Hoegh-Guldberg and Salvat, 1995; Loya et al., 2001), the exchange of genetic clades of *Symbiodinium* with more tolerant varieties (Baker, 2001; Jones et al., 2008), as well as acclimatization phenomena (Howells et al., 2012).

Studies of the thermal sensitivity of deeper-living cold-water corals (without endosymbionts) are scarce. One species, *Lophelia pertusa*, responds to about 3°C warming with a threefold increase in metabolic rate (Dodds et al., 2007), indicating a narrow thermal window in the cold (cf. Pörtner, 2006).

6.3.1.5. Ecosystems

Heat exposure of ecosystem engineers may threaten the existence of a whole ecosystem. During the last warm interglacial period equatorial coral reefs deteriorated and retreated (Kiessling et al., 2012), a finding emphasizing their thermal sensitivity (Veron et al., 2009) and showing that warming oceans can reach temperatures well beyond the upper heat limits of distinct animal groups and marine animals overall (Figure 6-6). In the present-day Great Barrier Reef, a large-scale survey found diverse coral types along a climatic gradient, with no consistent response to climatic drivers (Hughes et al., 2012). However, warm-induced bleaching has contributed to the progressive decrease in live coral cover observed over the last decades (De'ath et al., 2012; see also Box CC-CR; Section 30.5.6).

Within ecosystems, shifting competitive or trophic interactions, differential risks for species extinctions and, thereby, scenarios of community-level responses to temperature change (Urban et al., 2012; Milazzo et al., 2013) can be traced back to changing differences in the performance of participating animal species (Figure 6-7; e.g., Cairns et al., 2008; Harley, 2011; Pörtner, 2012). Knowledge is insufficient to assess interactions of species from different domains, impeding a deeper understanding of shifting distributions, abundances, community assemblages, and food webs in space and time (*low confidence* in current understanding; Parmesan and Matthews, 2005).

For example, in a coastal microcosm (small-scale, simplified experimental ecosystem) resident heterotrophic bacteria were stimulated by warming more than a laboratory-reared phytoplankter (Wohlers-Zöllner et al., 2011). Also, high- to low-latitude transects in both the North and South Atlantic revealed a shift between cold and warm waters, from photo-autotrophs (gaining energy from photosynthesis) to chemo-heterotrophs (Hoppe et al., 2002). Thermal stimulation of bacteria over phytoplankton has biogeochemical implications, for example, microbially mediated CO_2 flow to the atmosphere might increase (Sarmento et al., 2010). The principles and wider applicability of these findings require further investigation (*limited evidence*, *low agreement*; Kirchman et al., 2009).

Observations of shifting distributions and phenologies, reproduction, and range shifts of phytoplankton, zooplankton, other invertebrates, fishes, and seabirds in pelagic and coastal marine ecosystems have at least partly been attributed to temperature-mediated biological responses (*high confidence*; see also Figure 6-8; Box 6-1; Box CC-MB). In the North Atlantic as a key example, many biological events have been occurring earlier in the year (*robust evidence*, *high agreement*; Box 6-1; Section 30.5.1.1.1). Species richness has increased as a result of shifts in ranges and abundances. In the Norwegian and Barents Seas, a time series (1959–2006) of four commercial fish species and their zooplankton prey showed that climate shapes population growth rates through complex influences early in life, including direct temperature effects on growth, indirect effects via the biomass of zooplankton prey, and delayed feedback effects through predators (Stige et al., 2010). Differential species responses to temperature and trophic amplification were demonstrated to modify species interactions at five trophic levels: primary producers (phytoplankton); primary, secondary, and tertiary consumers (zooplankton, fishes, and jellyfishes); and benthic detritivores (echinoderms and bivalves) (Kirby and Beaugrand, 2009). Also, the responses of various plankton functional groups, such as diatoms, dinoflagellates, and copepods, to warming are not synchronous, resulting in predator-prey mismatches that carry over to higher trophic levels (*high confidence*; Edwards and Richardson, 2004; Costello et al., 2006; see also Figure 6-7a; Section 6.3.6). In the intertidal, warming-induced changes in relative species ranges lead to shifts in dominance through competitive interactions and to modifications in predator pressure (Poloczanska et al., 2008; Harley, 2011). Trans-Arctic interchange of species between Atlantic and Pacific has happened repeatedly in warm periods of the Pleistocene (Dodson et al., 2007) and may occur again, now facilitated by ballast transport by enhanced trans-Arctic shipping (*low* to *medium confidence*).

Warming may increase the risk of disease outbreaks or parasite infections, in marine organisms and ecosystems, and ultimately, humans (*medium*

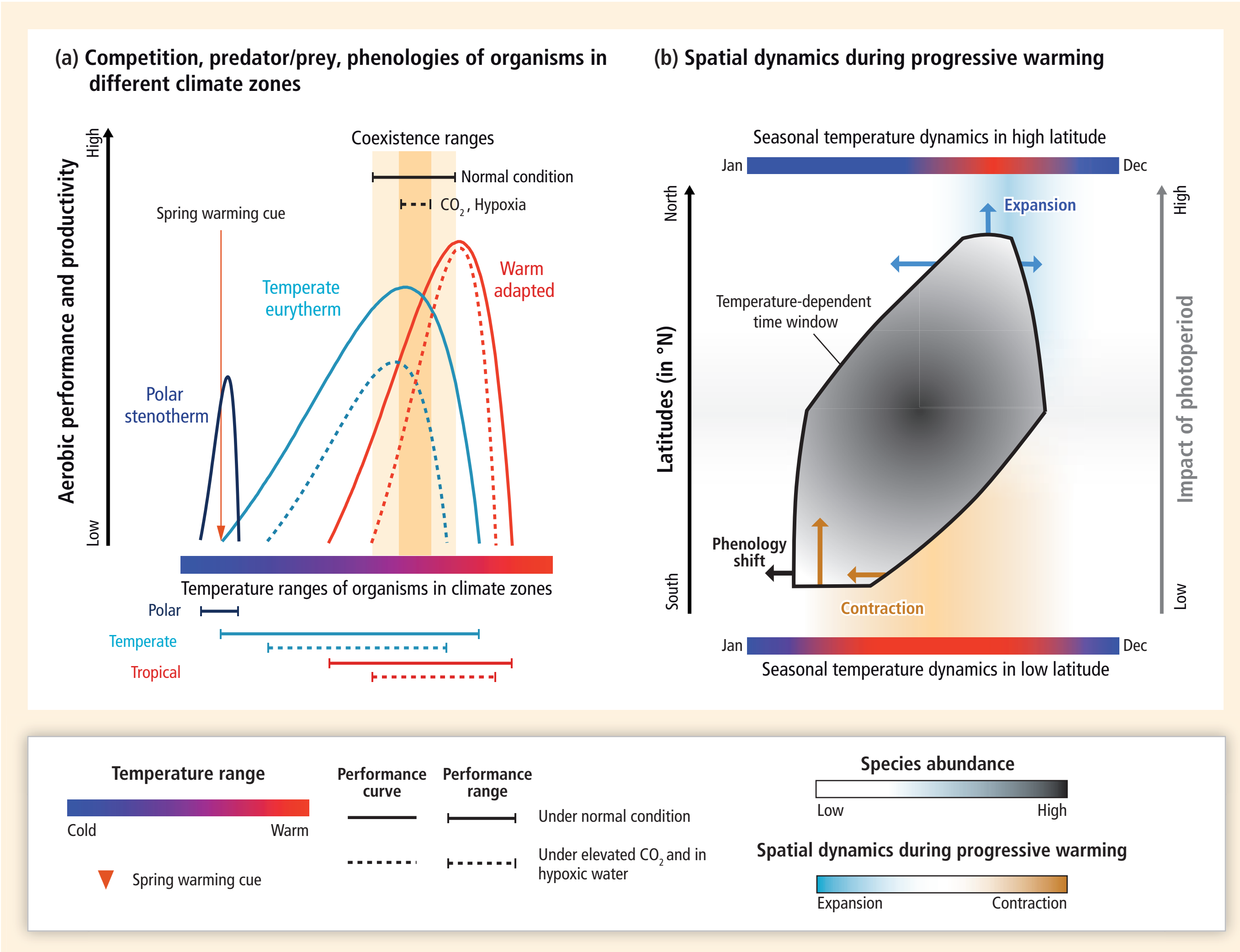


Figure 6-7 | Role of thermal tolerance and performance of organisms at ecosystem level. (a) Thermal tolerance ranges (Figure 6-5) differ between species across polar, temperate, and tropical climate zones, then overlap between coexisting species. Shifting temperatures and specific effects of additional drivers on the respective performance curves (dashed lines) change the fitness of coexisting species relative to each other as well as their temperature range of coexistence (after Pörtner and Farrell, 2008). Warming alters the timing of seasonal activities (e.g., elicited by spring warming cues) to earlier, or can benefit only one of two interacting species (e.g., in predator–prey dynamics or competition), causing shifts in predominance. (b) During climate warming a largely unchanged thermal range of a species causes it to follow its normal temperatures as it moves or is displaced, typically resulting in a poleward shift of the biogeographic range (exemplified for the Northern Hemisphere; modified after Beaugrand, 2009). The polygon delineates the distribution range in space and seasonal time; the level of gray denotes abundance. The Southern time window of tolerated temperatures shifts to earlier and contracts, while the Northern one dilates (indicated by arrows). Species display maximum productivity in low latitude spring, wide seasonal coverage in the center, and a later productivity maximum in the North. The impact of photoperiod (length of daily exposure to light) increases with latitude (gray arrow). Water column characteristics or photoperiod may overrule temperature control in some organisms (e.g., diatoms), limiting northward displacement.

confidence; Altizer et al., 2013; Burge et al., 2014). Some marine pathogens and protist diseases are shifting their distribution poleward as oceans warm (e.g., Baker-Austin et al., 2013; Burge et al., 2014). Climate change may weaken the immune response of hosts, particularly fishes and invertebrates, and increase their susceptibility to disease, as observed during warming in coral reefs of the Pacific and Caribbean (Harvell et al., 2009). Global outbreak frequencies of jellyfish aggregations may follow rising sea surface temperatures (SSTs) (*low confidence*; Mills, 2001; Purcell and Decker, 2005), but evidence is inconclusive. Some studies report an increasing trend (Brotz et al., 2012) and others do not support this view (Condon et al., 2013).

In conclusion, organisms live in limited temperature ranges and are sensitive to temperature extremes (*very high confidence*). Temperature governs the biogeography, diversity, development, reproduction, behavior, and phenology of marine species as well as the composition of communities in both pelagic and benthic systems and the seasonal timing of relevant processes (phenology) (*very high confidence*). Ecosystems functioning at the coldest temperatures and warm adapted ones existing at their upper thermal limits are more sensitive (*medium confidence*).

6.3.2. Carbon Dioxide Effects

Evidence for biological effects of ocean acidification stems from paleo-observations (Section 6.1.2), few observations in the field (Section 6.3.2.5), studies at volcanic CO_2 seeps as natural analogs, and mostly from short- to medium-term (hours to months) experiments in the

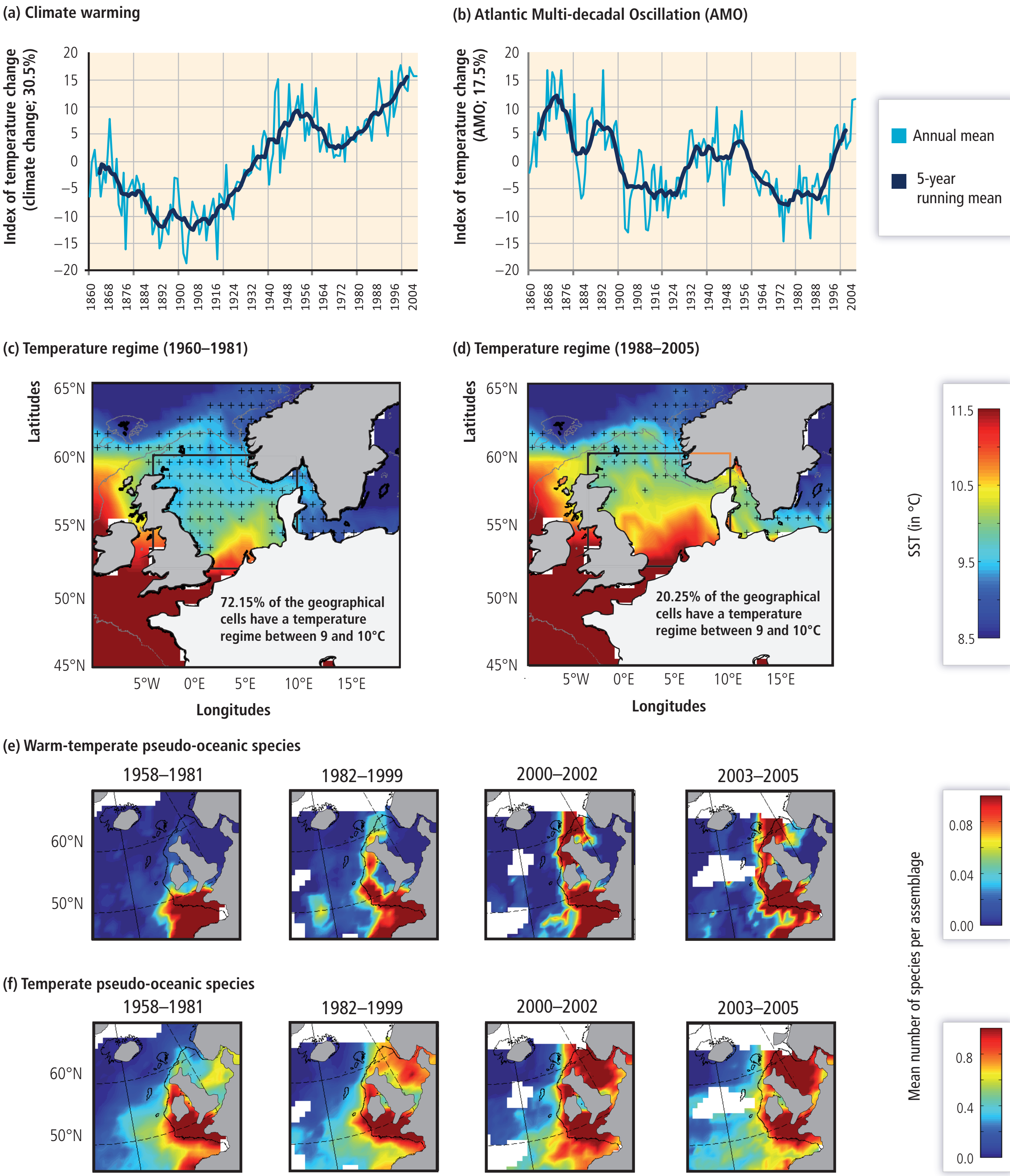
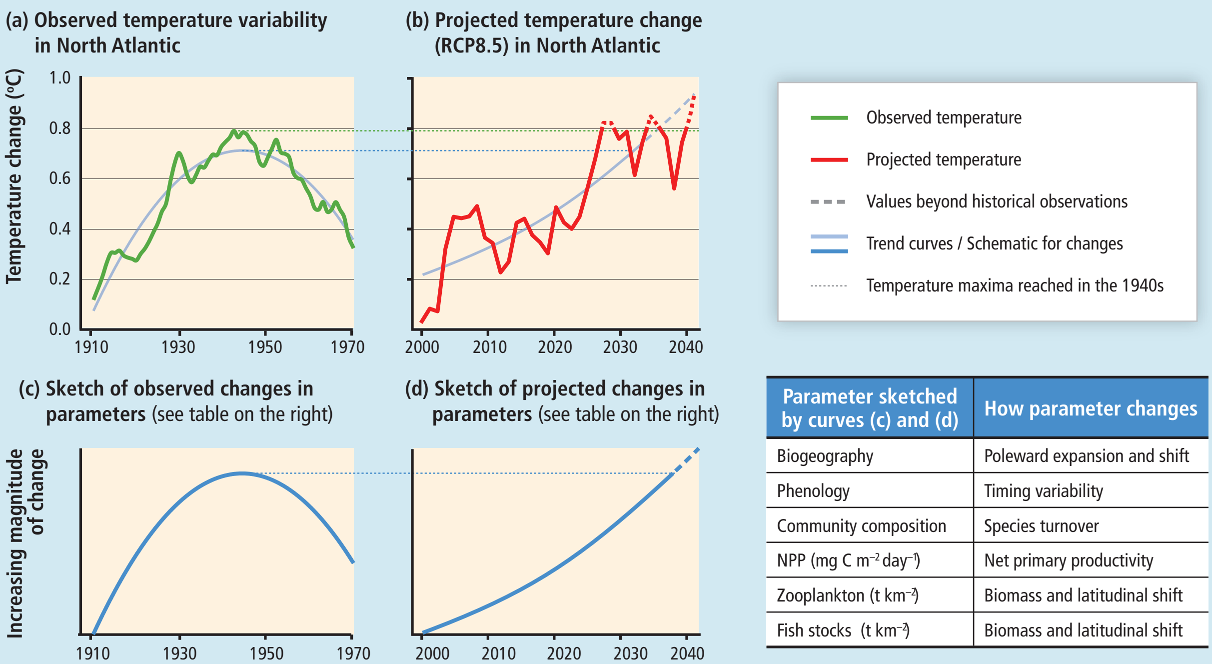


Figure 6-8 | Multi-decadal changes in ecosystem structure in the Northeast Atlantic driven by warming from both anthropogenic climate change and natural climate variability. (a) Index of temperature change over the North Atlantic (31°N to 65°N and 99°W to 11°E) reflecting climate change. This index is the first principal component (i.e., explaining 30.5% of observed variability) based on a principal component analysis (PCA) performed on sea surface temperature. (b) Index of temperature change (17.5% of observed variability) reflecting the Atlantic Multi-decadal Oscillation (AMO). The index is the second principal component. (c, d) Observed mean annual sea surface temperature in the North Sea during 1960–1981 (c) and 1988–2005 (d). The location of the critical thermal boundary (9°C to 10°C) is indicated by "+." (e) Long-term changes in the mean number of warm-temperate pseudo-oceanic species from 1958 to 2005. (f) Long-term changes in the mean number of temperate pseudo-oceanic species from 1958 to 2005. The period 1958–1981 was a period of relative stability and the period 1982–1999 was a period of rapid northward shifts, indicating that the abrupt ecosystem shift observed in the North Sea was part of a large-scale response of the zooplankton biodiversity to warming temperatures (see a–d). Average values are below 1 because they are annual averages. Note that the color bar is 10-fold smaller for warm-temperate pseudo-oceanic species because these species are less frequently observed than their temperate counterparts. Panels (a) and (b) from Edwards et al. (2013), and (c)–(f) from Beaugrand et al. (2008, 2009).

Box 6-1 | An Atlantic Ocean Example: Long-Term Responses of Pelagic Organisms and Communities to Temperature

Long-term observations (Sections 6.1.2, 30.5.1.1.1) encompassing the pelagic Northeast Atlantic over a 50-year period and longer (Figures 6-8, 6-9) show changes in the seasonal abundance of phytoplankton, rapid northerly displacements of temperate and subtropical zooplankton (e.g., calanoid copepods) and phytoplankton (e.g., dinoflagellates and diatoms), and the resulting changes in the ecosystem functioning and productivity (*high confidence*; Edwards et al., 2001; Beaugrand et al., 2002; Edwards and Richardson, 2004). The range limit of warm water copepods shifted by 10° north since 1960 (Beaugrand et al., 2009), with attendant mismatch in the seasonal timing of trophic levels (predators and prey) and functional groups (Edwards and Richardson, 2004). Modes of climate variability reflected in climate indices like the Northern Hemisphere Temperature (NHT) and the North Atlantic Oscillation (NAO) over multi-decadal periods accompanied these changes (Figure 6-1). In cooler regions, increased phytoplankton activity caused by warming favored growth, resulting in the observed increase in phytoplankton biomass, whereas a decrease in nutrient supply would have prevented growth in warmer regions and caused a decrease in biomass (Richardson and Schoeman, 2004; see also Section 6.3.4). Hinder et al. (2012) attributed a recent decline in North Sea dinoflagellates relative to diatoms to warming, increased summer windiness, and thus water column turbulence. The ecosystem response to natural climate variability in the past provides a glimpse into the climate-induced changes of the near future (Figure 6-9).



Parameter sketched by curves (c) and (d)	How parameter changes
Biogeography	Poleward expansion and shift
Phenology	Timing variability
Community composition	Species turnover
NPP (mg C m^{-2} day^{-1})	Net primary productivity
Zooplankton (t km^{-2})	Biomass and latitudinal shift
Fish stocks (t km^{-2})	Biomass and latitudinal shift

Figure 6-9 | Schematic depiction of observed effects of approximately 1°C ocean warming in the northern North Atlantic driven by climate variability (a,c) versus effects expected from anthropogenic climate change (b,d). (a) Transient warming and cooling associated with Atlantic Multi-decadal Oscillation (AMO) variability (Drinkwater, 2006), based on the Kola Section temperatures (0 to 200 m; Stations 3 to 7, 71.5° to 72.5°N, 33.5°E) in the Barents Sea obtained from http://www.pinro.ru and filtered using a 20-year running mean. Similar trends occurred across most of the northern North Atlantic although the amplitude and timing of the peaks and troughs varied spatially. (b) Warming driven by climate change for the same region (Representative Concentration Pathway 8.5 (RCP8.5) simulations averaged from Coupled Model Intercomparison Project Phase 5 (CMIP5) models, computed as the mean over the upper 200 m in the grid box (2.5° × 2.5°) centered at 71.25°N and 33.75°E). (c) Warming and subsequent cooling in the northern North Atlantic during the period shown in (a) resulted in complex multi-faceted changes (shown schematically) in net primary production (NPP), zooplankton biomass, and fish stock abundances. There was a general poleward shift and range expansion of many commercial (e.g., Atlantic herring, Atlantic cod, haddock) and non-commercial species, reversed during the subsequent cooling period. Poleward shifts in spawning areas (e.g., Atlantic cod) were also reversed as the waters cooled. Shifts in seasonal timing (phenology) and community composition were influenced by earlier arrivals and later retreat of migratory fish (not shown). For more details see Drinkwater (2006). (d) Projected effects of climate mediated warming on northern sub-polar and polar biota based on model projections of altered NPP (Bopp et al., 2013), and of the range shift of exploited fishes and invertebrates (Cheung et al., 2009, 2013a). The projected trends in (d) will differ with latitude, for example, decreased NPP at lower latitudes and no significant change to NPP in temperate waters (Bopp et al., 2013). Higher NPP supported and is projected to support higher trophic levels at high latitudes (c,d; Section 6.3.4). Note that climate variability will be superimposed on anthropogenic warming (b; see Figures 6-1, 6-8a,b). Dashed lines indicate projected changes to continue beyond the range of historical observations.

Continued next page →

Box 6-1 (continued)

In regions of high vulnerability to climate, mild warming can trigger rapid and substantial ecosystem shifts, offering a way to anticipate future changes (Figure 6-9). In line with the increased understanding of physiology (Section 6.3.1.1), warming in the temperate to polar North Atlantic was paralleled by a reduction in the average body lengths of about 100 copepod species, from 3 to 4 mm to 2 to 3 mm (Beaugrand et al., 2010). Warming also correlated with an increase in species richness among copepods and within the dinoflagellate genus *Ceratium*. In diatoms, which are major contributors to carbon export (Armbrust, 2009), warming and decreasing annual variability in SST resulted in lower diversity, smaller size, and reduced abundance (Beaugrand et al., 2010). Morán et al. (2010) found that temperature alone explained 73% of the variance in the contribution of small cells (picophytoplankton) to total phytoplankton biomass in the eastern and western temperate North Atlantic from –0.6 to 22°C. More recently, Marañón et al. (2012) analyzed data from polar, sub-polar, and tropical regions and suggested that nutrient availability may influence cell size more than temperature.

The ecosystem regime shift observed in North Sea plankton in the late 1980s involved an increase in phytoplankton stocks and changes in species composition and abundance among holozooplankton (animals that are planktonic for their entire lifecycle) (Reid et al., 2001; Kirby and Beaugrand, 2009; Kirby et al., 2009; Lindley et al., 2010). This shift was paralleled by the northward propagation of a critical thermal boundary (CTB, i.e., the boundary of the sub-polar gyre) between the temperate and the polar biomes (Beaugrand et al., 2008; see also Box CC-PP, Figure 1). Warming to above the CTB coincided with pronounced and large-scale variations in phytoplankton productivity, an increase in calanoid copepod diversity (Beaugrand et al., 2008) and herring abundance (Schlüter et al., 2008), a reduction in the mean size of calanoids, and a decrease in the abundance of southern Atlantic cod populations in the North Atlantic Ocean (e.g., the North Sea; Pörtner et al., 2008; Beaugrand et al., 2010). These patterns also extend to the southern North Sea, where elevated salinities and average warming by 1.6°C, both in summer and winter between 1962 and 2007, expanded the time window for growth of microalgae and possibly supported the invasion and increase in numbers of warm-adapted silicified diatoms (Wiltshire et al., 2010). Recent findings indicate a regime shift in the Bay of Biscay and the Celtic and the North Seas in the mid to end 1990s (Luczak et al., 2011). Changing plankton composition and changing abundances of both sardine and anchovies (Raab et al., 2013) paralleled stepwise warming.

Northward range extensions or redistributions in fishes were largest along the European Continental shelf and attributed to regional warming, for example, by 1.0°C from 1977 to 2001 in the North Sea, with winter warming being closely correlated with the shift of Atlantic cod (Perry et al., 2005; see also Section 6.3.1). Similar trends were observed due to warming by 1°C to 2°C in the waters south and west of Iceland during the past 15 years (Valdimarsson et al., 2012). In the Northwest Atlantic Arctic and sub-Arctic, winter and spring warming caused expansion of the area matching the thermal optimum of Atlantic salmon at 4°C to 8°C and caused greater growth (Friedland and Todd, 2012). Pelagic sardines and anchovies entered the North Sea in the early to mid-1990s, after about 40 years of absence, in response to intensified NAO and AMO (Alheit et al., 2012). Red mullet and bass extended into western Norway; Mediterranean and northwest African species extended to the south coast of Portugal (Brander et al., 2003; Beare et al., 2004; Genner et al., 2004; see also Section 30.5.1.1.4).

In the Northwest Atlantic cooling and freshening occurred during the late 1980s to early 1990s and seemed to have the opposite effect, as capelin and their predator, Atlantic cod, shifted farther south (Rose and O'Driscoll, 2002). Between the early 1990s and mid-2000s in the Northwest Atlantic sub-polar gyre, phytoplankton biomass increased, due to warming. At the same time, Arctic copepod species became more abundant, due to increased influx of Arctic water (Head and Pepin, 2010). Although temperatures have risen on the Newfoundland Shelf (Colbourne et al., 2011), capelin and cod remain scarce for reasons probably unrelated to climate (DFO, 2011a,b). Farther south, Arctic freshwater inflows caused freshening and increased stratification of the area around the Gulf of Maine throughout the 1990s, resulting in enhanced phytoplankton abundance, a larger and later fall bloom, increased abundance of small copepods, and a decrease in the large copepod *Calanus finmarchicus* (deYoung et al., 2004; Pershing et al., 2005, 2010). Various fish species showed poleward shifts in distribution (Table 6-2) that were associated with reduced survival of larval cod (Mountain and Kane, 2010) and fewer right whale calves (Greene et al., 2003), but increased herring abundance (Greene and Pershing, 2007).

Frequently Asked Questions

FAQ 6.3 | Why are some marine organisms affected by ocean acidification?

Many marine species, from microscopic plankton to shellfish and coral reef builders, are referred to as calcifiers, species that use solid calcium carbonate ($CaCO_3$) to construct their skeletons or shells. Seawater contains ample calcium but, to use it and turn it into $CaCO_3$, species have to bring it to specific sites in their bodies and raise the alkalinity (lower the acidity) at these sites to values higher than in other parts of the body or in ambient seawater. That takes energy. If high CO_2 levels from outside penetrate the organism and alter internal acidity levels, keeping the alkalinity high takes even more energy. The more energy is needed for calcification, the less is available for other biological processes such as growth or reproduction, reducing the organisms' weight and overall competitiveness and viability.

Exposure of external shells to more acidic water can affect their stability by weakening or actually dissolving carbonate structures. Some of these shells are shielded from direct contact with seawater by a special coating that the animal makes (as is the case in mussels). The increased energy needed for making the shells to begin with impairs the ability of organisms to protect and repair their dissolving shells. Presently, more acidic waters brought up from the deeper ocean to the surface by wind and currents off the Northwest coast of the USA are having this effect on oysters grown in aquaculture.

Ocean acidification affects not only species producing calcified exoskeletons. It affects many more organisms either directly or indirectly and has the potential to disturb food webs and fisheries. Most organisms that have been investigated display greater sensitivity at extreme temperatures so, as ocean temperatures change, those species that are forced to exist at the edges of their thermal ranges will experience stronger effects of acidification.

laboratory or field, exposing organisms to projected future CO_2 levels (Sections 6.3.2.1-4). A surging number of studies is providing evidence that rising CO_2 levels will increasingly affect marine biota and interfere with ecological and biogeochemical processes in the oceans (*high confidence*; FAQs 6.2, 6.3).

6.3.2.1. Principles

The absorption of rising atmospheric CO_2 by oceans and organisms changes carbonate system variables in the water and in organism internal fluids, that is, the relative proportions of CO_2, carbonate, bicarbonate, and hydrogen ions (pH). Internal pH must be tightly controlled, as some processes, such as calcification, release protons thereby affecting pH and as other biochemical processes are pH sensitive. Accumulation of CO_2 and the resulting acidification can also affect a wide range of organismal functions, such as membrane transport, calcification, photosynthesis in plants, neuronal processes in animals, growth, reproductive success, and survival. Effects translate from organism to ecosystem.

The capacity of organisms to resist and compensate for the CO_2-induced acidification of internal fluids depends on acid-base regulation, that is, the capacity of ion exchange to accumulate bicarbonate internally, an aspect unexplored in many phyla (*low* to *medium confidence*; Figure 6-10a; e.g., animals: Heisler, 1986; Claiborne et al., 2002; Pörtner, 2008; phytoplankton: Taylor et al., 2011; see also FAQ 6.3).

In unicellular microbes the regulation of intracellular pH may play a key role in modulating CO_2 responses (Taylor et al., 2011). Findings in invertebrates and fish indicate an additional role for extracellular pH (Figure 6-10a); effective pH values may vary between species. Organisms pre-adapted to elevated CO_2 may minimize the decrease in pH (acidosis). They may also modify their sensitivity such that they respond less or not at all to the acidosis. Recent evidence, however, emphasizes a role for acid-base regulation in a natural low-pH setting. Between two urchin species, only the one successful in maintaining its setpoints of extracellular pH is able to settle close to volcanic CO_2 seeps (Calosi et al., 2013). Compensating for the acidosis may cause increased energy demand and respiration rates. In general, such capacity rises with metabolic energy turnover, for example, it is higher in more active marine animals, such as fishes, cephalopods, and pelagic copepods, and in mobile coastal crabs compared to sessile species (Pörtner et al., 2005, 2011; Ishimatsu et al., 2008; Melzner et al., 2009; Ishimatsu and Dissanayake, 2010; see also Table 6-3). This matches the sensitivity distribution seen among animals at the phylum level (*medium confidence*; Figure 6-9b).

Some species have lower metabolic rates in response to acidosis (Pörtner et al., 1998; Michaelidis et al., 2005; Pörtner, 2008; Liu and He, 2012; Navarro et al., 2013); others display increased energy turnover and food ingestion rates, possibly indicating a capacity to resist acidification effects (Parker et al., 2011; Saba et al., 2012). The effects of the acidosis on various processes relevant to fitness may explain changes in whole-organism energy demand, probably paralleled by modified ion exchange, protein synthesis, and growth and feeding rates. The magnitude of effect depends on the CO_2 concentrations reached (Figure 6-10b).

The internal formation of carbonate from bicarbonate is essential to calcification, which is the formation of solid $CaCO_3$ in internal or external calcified structures, used for defense and structural support. Calcification usually occurs in separate body or cell compartments, where pH and thus CO_3^{2-} concentration and saturation Ω (Section 6.1.1) are maintained at values higher than in other body fluids or ambient water (Taylor et al., 2011; Trotter et al., 2011; McCullough et al., 2012; Venn et al., 2013). CO_2 impedes the formation of carbonate such that calcification rate decreases. It may be maintained by enhanced transport of ions, incurring elevated energetic costs (Figure 6-10).

External carbonate structures like shells rely on ambient seawater being supersaturated with carbonates. Decreasing oceanic carbonate levels reduce the saturation levels (Ω) of calcite or aragonite in the water. Reduction to below unity may lead to the corrosion of carbonate shells (FAQ 6.3). However, many species protect their shells from direct contact with seawater by various types of organic coating (e.g., a periostracum in mollusks and brachiopods, an epicuticle covering the carapace of crustaceans, an epidermis covering the tests of urchins, epithelial tissue covering aragonite in corals, and coralline algae precipitating $CaCO_3$ (mostly Mg-calcite) within their cell wall). A meta-analysis of the effects of ocean acidification on biological processes indicates that reductions in the rate of net calcification (calcification minus dissolution) and survival are the most uniform responses across organisms studied, relative to other, more variable impacts such as reduced growth, development, and abundance (Kroeker et al., 2013; see also Box CC-OA).

Some organisms benefit from elevated CO_2 partial pressures (pCO_2). Photosynthesis and/or nitrogen fixation in selected microorganisms are impacted by OA, but effects are species or taxon specific, possibly depending on how they acquire carbon, that is, the presence and in particular the type, capacity, and energetic costs of carbon-concentrating mechanisms (CCMs; Giordano et al., 2005; Kranz et al., 2011).

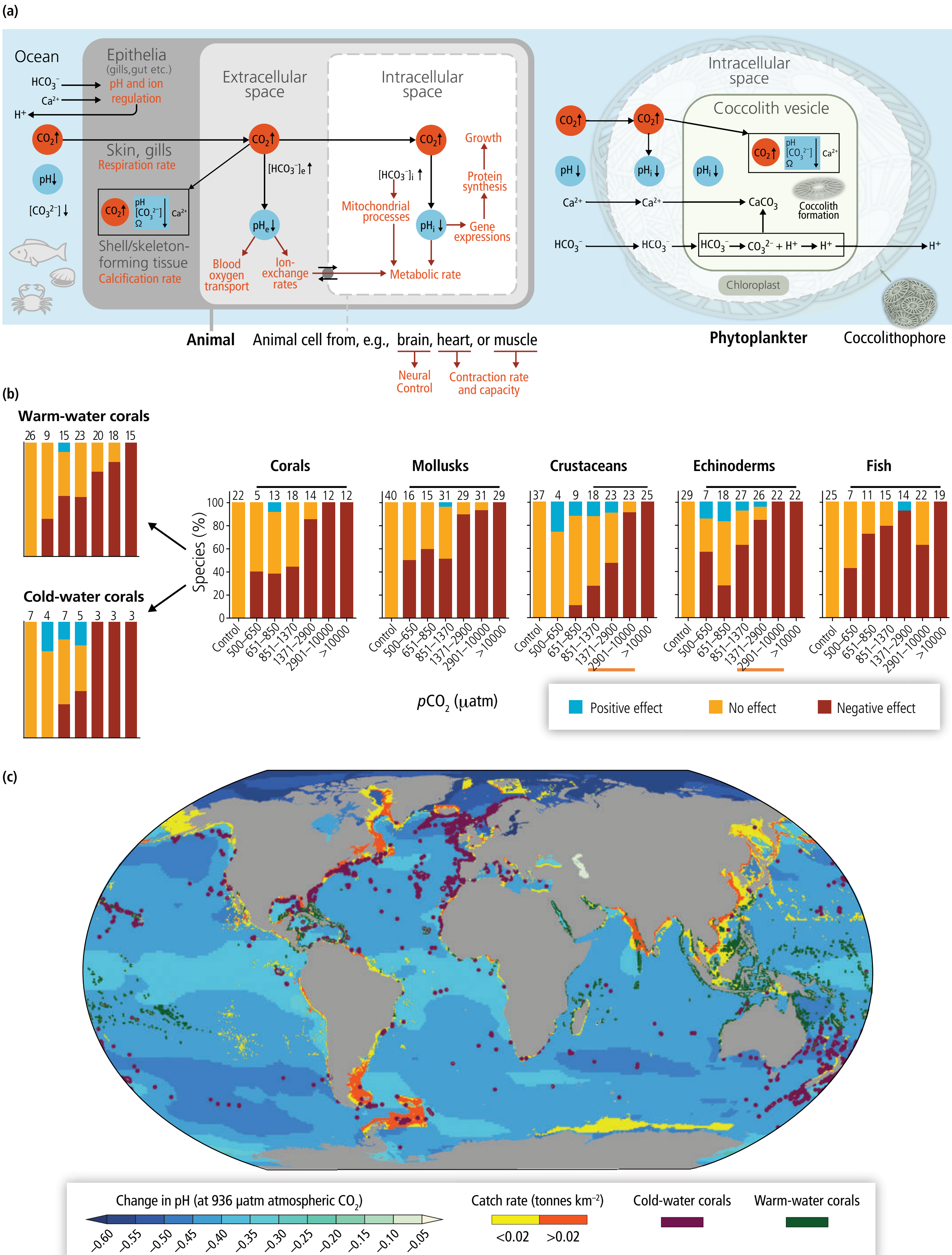
A comprehensive picture of responses to CO_2 requires consideration of variable sensitivities between species and life stages and taxon-specific sensitivity distributions, as shown by a meta-analysis of animal data (Wittmann and Pörtner, 2013; see also Figure 6-10b). Echinoderms, bivalves, gastropods, and corals begin to respond negatively at lower CO_2 levels than crustaceans or cephalopods (Figure 6-10b). This sensitivity

Table 6-3 | Tolerances to ocean acidification in marine taxa, assessed from laboratory and field studies of species in the CO_2 partial pressure (pCO_2) range from <650 to >10000 µatm, compared to present day atmospheric levels of 400 µatm. (It should be noted that anthropogenic CO_2 emissions add to the natural variability of CO_2 concentrations in marine environments, which can reach much higher than atmospheric levels.) Variables studied include growth, survival, calcification, metabolic rate, immune response, development, abundance, behavior, and others. Neither all life stages, nor all variables, including the entire range of CO_2 concentrations, were studied in all species. *Confidence* is based on the number of studies, the number of species studied, and the agreement of results within one group. + denotes that possibly more species or strains (genetically distinct populations of the same species) were studied, as only genus or family were specified; beneficial: most species were positively affected; vulnerable: more than 5% of species in a group will be negatively affected by 2100; tolerant: more than 95% of species will not be affected by 2100. RCP 6.0: Representative Concentration Pathway (RCP) with projected atmospheric pCO_2 = 670 µatm; RCP 8.5: pCO_2 = 936 µatm in 2100 (Meinshausen et al., 2011). *Confidence* is limited by the short- to medium-term nature of various studies and the lack of sensitivity estimates on evolutionary time scales, that is, across generations (see separate reference list, Online Supplementary Material). Note that the assessment of variability between species from the same animal phylum has revealed an increase in the fraction of sensitive species with rising CO_2 levels; see Figure 6-10.

Taxon	No. of studies	No. of parameters studied	Total no. of species studied	pCO_2 where the most vulnerable species is negatively affected or investigated pCO_2 range[a] (µatm)	Assessment of tolerance to RCP 6.0 (*confidence*)	Assessment of tolerance to RCP 8.5 (*confidence*)
Cyanobacteria	17	5	9+	180–1250[a]	Beneficial (*low*)	Beneficial (*low*)
Coccolithophores	35	6	7+	740	Tolerant (*low*)	Vulnerable (*medium*)
Diatoms	22	5	28+	150–1500[a]	Tolerant (*low*)	Tolerant (*low*)
Dinoflagellates	12	4	11+	150–1500[a]	Beneficial (*low*)	Tolerant (*low*)
Foraminifers	11	4	22	588	Vulnerable (*low*)	Vulnerable (*medium*)
Seagrasses	6	6	5	300–21000[a]	Beneficial (*medium*)	Beneficial (*low*)
Macroalgae (non-calcifying)	21	5	21+	280–20812[a]	Beneficial (*medium*)	Beneficial (*low*)
Macroalgae (calcifying)	38	10	36+	365	Vulnerable (*medium*)	Vulnerable (*high*)
Warm-water corals	45	13	31	467	Vulnerable (*medium*)	Vulnerable (*high*)
Cold-water corals	10	13	6	445	Vulnerable (*low*)	Vulnerable (*medium*)
Annelids	10	6	17+	1200	Tolerant (*medium*)	Tolerant (*medium*)
Echinoderms	54	14	35	510	Vulnerable (*medium*)	Vulnerable (*high*)
Mollusks (benthic)	72	20	38+	508	Vulnerable (*medium*)	Vulnerable (*high*)
Mollusks (pelagic)	7	8	8	550	Vulnerable (*low*)	Vulnerable (*medium*)
Mollusks (cephalopods)	10	8	5	2200 (850 for trace elements)	Tolerant (*medium*)	Tolerant (*medium*)
Bryozoans	7	3	8+	549	Tolerant (*low*)	Vulnerable (*low*)
Crustaceans	47	27	44+	700	Tolerant (*medium*)	Tolerant (*low*)
Fish[b]	51	16	40	700	Vulnerable (*low*)	Vulnerable (*low*)

[a]Rather than a sensitivity threshold the entire range of investigated pCO_2 values is given for groups of photosynthetic organisms. In all studies photosynthetic rates are stimulated to different, species-specific degrees by elevated pCO_2, indicating low vulnerability. Coccolithophores and calcifying algae are assessed as being more sensitive than other photosynthetic organisms due to reduced calcification and shell dissolution.

[b]Confidence levels for fishes were converted from medium to low, in light of uncertainty on the long-term persistence of behavioral disturbances.


(a)
Ocean
HCO_3^-
Ca^{2+}
H^+
CO_2↑
pH↓
$[CO_3^{2-}]$↓
Epithelia
(gills,gut etc.)
pH and ion regulation
Skin, gills
Respiration rate
Shell/skeleton-forming tissue
Calcification rate
Extracellular space
$[HCO_3^-]_e$↑
pH_e↓
Blood oxygen transport
Ion-exchange rates
Intracellular space
$[HCO_3^-]_i$↑
Mitochondrial processes
pH_i↓
Growth
Protein synthesis
Gene expressions
Metabolic rate
Animal
Animal cell from, e.g., brain, heart, or muscle
Neural Control
Contraction rate and capacity
Intracellular space
Coccolith vesicle
$CaCO_3$
Coccolith formation
HCO_3^- → CO_3^{2-} + H^+ → H^+
Chloroplast
Phytoplankter
Coccolithophore
(b)
Warm-water corals
26 9 15 23 20 18 15
Cold-water corals
7 4 7 5 3 3 3
Corals
22 5 13 18 14 12 12
Mollusks
40 16 15 31 29 31 29
Crustaceans
37 4 9 18 23 23 25
Echinoderms
29 7 18 27 26 22 22
Fish
25 7 11 15 14 22 19
Species (%)
100 80 60 40 20 0
Control 500–650 651–850 851–1370 1371–2900 2901–10000 >10000
pCO_2 (µatm)
Positive effect
No effect
Negative effect
(c)
Change in pH (at 936 µatm atmospheric CO_2)
–0.60 –0.55 –0.50 –0.45 –0.40 –0.35 –0.30 –0.25 –0.20 –0.15 –0.10 –0.05
Catch rate (tonnes km^{-2})
<0.02 >0.02
Cold-water corals
Warm-water corals

6

Figure 6-10 | (a) Responses of a schematized marine animal (left) and a phytoplankter (right) to ocean acidification. Effects are mediated via diffusive CO_2 entry (black arrows) into body and cell compartments, resulting in a rise in pCO_2 (highlighted in red), a drop in compartmental pH (highlighted in blue), and their effects (red arrows) on various processes (red text) in tissues and cellular compartments, as well as on calcium carbonate saturation state (Ω) at calcification sites (after Pörtner, 2008; Taylor et al., 2011). Variable sensitivity relates to the degree of pH decline and compensation, depending on the capacity of pH and ion regulation. (b) Distribution of sensitivities across species within animal phyla, under progressively rising water CO_2 levels, as percent of studied cold- and warm-water coral (mostly scleractinia), echinoderm, molluskan, crustacean, and fish species affected negatively, positively, or not at all (for effects considered, see text). As not all life stages, variables, and pCO_2 ranges were covered in all species, two assumptions partially compensate for missing data: 1) Negative effects at low pCO_2 will remain negative at high pCO_2. 2) A positive or neutral outcome at both low and high pCO_2 will be the same at intermediate pCO_2. As responses reported for each species vary for each pCO_2 range, variable species numbers result (on top of columns). The total number of species studied in a group is shown as the number above the control column. The control category corresponds to 380 µatm. For 2100, RCP scenarios falling within each CO_2 partial pressure (pCO_2) category are as follows: RCP4.5 for 500–650 µatm (approximately equivalent to ppm in the atmosphere), RCP6.0 for 651–850 µatm, and RCP8.5 for 851–1370 µatm. By 2150, RCP8.5 falls within the 1371–2900 µatm category. Horizontal lines above columns represent frequency distributions significantly different from controls (Wittmann and Pörtner, 2013). Data for warm- and cold-water corals as in Table 6-3. (c) Areas with reported annual catches of marine calcifiers (crustaceans and mollusks) ≥ 0.005 tonnes km^{-2} depicted on a global map (weighted mean of the orange color area =0.07 tonnes km^{-2}) showing the distribution of ocean acidification in 2100 according to RCP8.5 (WGI AR5 SPM; pH change from 1986–2005 to 2081–2100) as well as the distribution of warm-water (green dots) and cold-water coral communities (purple dots).

pattern resembles the one seen in the Permian mass extinction (Knoll et al., 2007; Knoll and Fischer, 2011). The picture for fishes is less clear, as the present findings of high vulnerability are not met by similar observations in the fossil record. Evolutionary adaptation may thus eliminate or minimize reported effects.

The capacity for pH and ion regulation and other relevant processes can be upregulated by gene expression, as seen in acclimation studies in echinoderm larvae (O'Donnell et al., 2010; Martin et al., 2011) and fishes (Deigweiher et al., 2008; Tseng et al., 2013), in warm-water coral branches (Kaniewska et al., 2012), but not in a study of warm-water coral larvae (Moya et al., 2012). Few studies address whether and to what extent species undergo evolutionary adaptation to high pCO_2, as seen in the coccolithophore *Emiliania huxleyi* over 500 asexual generations (Lohbeck et al., 2012). In organisms with longer generation times, perturbation studies in the laboratory measure tolerance and acclimation, but not adaptation or natural selection. Animal adaptation is accelerated by high functional variability among larvae, enabling selection of resistant genotypes (*low* to *medium confidence*; Sunday et al., 2011; Parker et al., 2012; Pespeni et al., 2013). This may explain the selective mortality seen in Atlantic cod larvae under elevated CO_2 (Frommel et al., 2012). Both acclimatization and adaptation will shift sensitivity thresholds but the capacity and limits of species to acclimatize or adapt remain largely unknown and hence impacts of acute exposures cannot easily be scaled up to effects on the longer, evolutionary time scales of ocean acidification (Wittmann and Pörtner, 2013). Observations in ecosystems characterized by permanently elevated or fluctuating CO_2 levels, such as upwelling areas, OMZs (Section 6.1.1), or seeps, reflect the existence of sensitivity thresholds (*high confidence*; Section 6.3.2.5) but organisms may have evolved a higher resistance to increased CO_2 levels than elsewhere (*low confidence*).

Table 6-3 compiles effects of ocean acidification observed across taxa in laboratory and field experiments. The latter include studies in mesocosms and at natural analogs, submarine CO_2 venting areas at locales such as Ischia, Italy (Hall-Spencer et al., 2008), Papua New Guinea (Fabricius et al., 2011), and Puerto Morelos, Mexico (Crook et al., 2012). It should be noted that anthropogenic CO_2 accumulation according to RCPs adds to the natural variability of CO_2 concentrations in marine environments. Many groups, especially sessile or non-photosynthetic calcifiers, have sensitive species with vulnerability thresholds surpassed under RCP6.0 by 2100 (*low* to *medium confidence*).

Recent meta-analyses also summarize OA effects, two for biogeochemical processes and relative effect sizes (Harvey et al., 2013; Kroeker et al., 2013), one for the distribution of sensitivity between species within major animal phyla and its change depending on ambient pCO_2 (Figure 6-10; Wittmann and Pörtner, 2013). All of these analyses consider the interaction of warming and CO_2 accumulation (Section 6.3.5). Present limitations in understanding the mechanisms of effect and their long-term persistence compounds accurate projections of the long-term effects of OA (*medium confidence*; Wittmann and Pörtner, 2013).

6.3.2.2. Microbes

The physiology of both calcifying (coccolithophores) and non-califying phytoplankton can be influenced by changes in carbonate system variables caused by ocean acidification (Figure 6-10a). Growth and photosynthetic rates of diatoms in laboratory cultures are considered relatively insensitive to elevated CO_2 (Rost et al., 2003; Trimborn et al., 2008). Dinoflagellate sensitivity to elevated CO_2 is poorly studied (Hansen et al., 2007), but in one species carbon fixation rates were enhanced at 750 µatm CO_2 while growth remained unaffected (Fu et al., 2008). Indirect effects of ocean acidification on phytoplankton physiology include altered availability of trace metals needed for many biochemical cycles (Hoffmann et al., 2012).

Harmful algal blooms are a growing problem in coastal waters worldwide (Section 6.4.2.3), and many of the various phytoplankton species that produce bio-accumulated toxins are sensitive to changes in the seawater carbonate buffer system (Hallegraeff, 2010; Fu et al., 2012). For example, the dominance and community structure of harmful bloom dinoflagellates can be profoundly altered by changing pCO_2 (Tatters et al., 2013), and both toxic dinoflagellates and diatoms have been shown to produce higher toxin levels under near-future levels of ocean acidification (Fu et al., 2010; Sun et al., 2011).

Some planktonic N_2-fixing cyanobacteria (diazotrophs), for example, strains (genetically distinct populations of the same species) of offshore cyanobacteria of the genera *Trichodesmium* and *Crocosphaera*, respond to rising CO_2 with increased rates of both carbon and N_2 fixation (Fu et al., 2008; Lomas et al., 2012). In contrast, laboratory studies using the bloom-forming cyanobacteria *Nodularia* (an organism largely found in coastal stratified, eutrophic waters) revealed decreased growth and N_2

fixation under elevated CO_2 conditions (Czerny et al., 2009). The wide range of responses in N_2 fixation (e.g., Hutchins et al., 2007; Levitan et al., 2007; Kranz et al., 2010) may be explained by different CO_2 affinities (i.e., dependences of growth rates on CO_2 concentration) of a range of N_2-fixing cyanobacteria (*Trichodesmium* and *Crocosphaera*) from different oceanic biomes. Some species/strains operate at close to maximum growth rates at present-day oceanic CO_2 levels, whereas others had sub-optimal growth rates under these conditions (Hutchins et al., 2013). To date, the physiological mechanisms underlying these responses remain unknown, especially in open-ocean nitrogen fixers. Cyanobacteria may reallocate energy from their energetically expensive CCMs toward N_2 fixation and the acquisition of growth limiting nutrients (Kranz et al., 2010; Levitan et al., 2010), but evidence for such diversion of energy is lacking. Whether nitrogen fixation will increase with progressive ocean acidification remains to be explored (*low confidence*, *limited* in situ *evidence*, *medium agreement*).

The responses of coccolithophore calcification to OA are species specific and highly variable. The function(s) of calcification are not well understood, making it difficult to evaluate the consequences of lowered calcification (e.g., Rost et al., 2008). Reductions, increases, and unchanged calcification rates (and shell structure) have all been found in different coccolithophore species for RCP8.5 CO_2 conditions projected around 2100 (Riebesell et al., 2000; Zondervan et al., 2001; Langer et al., 2006; Iglesias-Rodriguez et al., 2008). Calcification in coccolithophores is species (Langer et al., 2006) and in *Emiliania huxleyi* even strain specific (Langer et al., 2009, 2011; Hoppe et al., 2011). It thus remains unclear whether OA will result in exoskeletons that are insufficiently calcified for sustained structural support and protection in coccolithophores (*medium evidence*, *low agreement*).

Foraminifera display decreasing calcification and shell weight under elevated CO_2 (Lombard et al., 2010). Changes in historical specimens (Moy et al., 2009; see Section 6.3.2.5.1) and during glacial-interglacial cycles (Barker and Elderfield, 2002) support projections of future reductions in net calcification by foraminifera (*medium* to *high confidence*).

6.3.2.3. Macroalgae and Seagrasses

Primary production, shoot density, reproductive output, and below-ground biomass of seagrasses generally respond positively to elevated pCO_2, indicating CO_2 limitation of their productivity. Such effects were identified in both laboratory and field above 720 to 1800 µatm (*high confidence*; e.g., Palacios and Zimmerman, 2007; Hall-Spencer et al., 2008; Andersson et al., 2011; cf. Section 5.4.2.3). Production, growth, and recruitment of most but not all non-calcifying seaweeds also increased at CO_2 levels from 700 to 900 µatm (RCP8.5; Porzio et al., 2011; Kroeker et al., 2013). Some non-calcifying seaweeds and seagrasses will thus benefit from future ocean acidification (*high confidence*) but OA exposes them to higher than usual grazing as a consequence of losing deterrent phenolic substances (*low confidence*; Arnold et al., 2012).

Calcifying algae (corallines) show complex and species-specific responses of photosynthesis to elevated CO_2, but calcification is impacted once species-specific pCO_2 thresholds are surpassed (*medium confidence*; Anthony et al., 2008; Martin and Gattuso, 2009). At habitat temperature calcification by temperate coralline red and calcareous green algae increased at CO_2 levels up to 900 µatm and decreased only at the highest concentration applied (2850 µatm), but did not fall below rates found at present-day pCO_2 (Ries et al., 2009). During 3 months of exposure, growth of *Lithothamnion glaciale*, a cold-water calcareous red alga, decreased progressively with rising CO_2 levels, and its structural integrity was weakened beyond 590 µatm (Ragazzola et al., 2012), potentially influencing ecosystem function. Some calcifying algae may thus be impacted by future ocean acidification (*medium confidence*).

6.3.2.4. Animals

Studies of marine animals and their life stages show a high diversity and variability of processes affected by ocean acidification. Many variables studied reflect physiological performance (O_2 consumption, exercise, behavior, calcification, growth, immune response, acid-base balance, gene expression, fertilization, sperm motility, developmental time, production of viable offspring, and morphology; Table 6-3; Figure 6-10). In some species growth may be stimulated by OA, in others depressed or unaffected (cf. Gooding et al., 2009; Munday et al., 2009a, 2011a; Dupont et al., 2010). The degree of CO_2-induced acidosis and its compensation by ion exchange may shape sensitivity (Section 6.3.2.1). Full exploitation of the ability to resist pCO_2 increases depends on the availability and high quality of food and the strengthening of fitness (Gooding et al., 2009; Melzner et al., 2011). However, food quality of prey organisms may decrease under elevated pCO_2. For example, slower reproduction and growth of the copepod *Acartia tonsa* under 760 µatm pCO_2 was related to the decreasing quality of its diatom food (Rossoll et al., 2012).

Changes in calcification rates reported from CO_2 manipulation experiments vary widely. Reduced calcification and weakened calcified structures were seen under elevated pCO_2 in corals (see Section 6.3.2.4.2), echinoderms (Kurihara and Shirayama, 2004), mollusks (Gazeau et al., 2013), and larval crustaceans (Arnold et al., 2009; Walther et al., 2011). Some adult limpets and urchins increased calcification rates at pCO_2 from 600 to 900 µatm, before it fell at even higher pCO_2. In some adult crabs, lobsters, and shrimps calcification rates increased further with rising pCO_2 (Ries et al., 2009). Stronger internal structures such as cuttlebones and otoliths resulted from enhanced calcification under elevated pCO_2 in juvenile cuttlefish (cephalopods: Gutowska et al., 2008) and fishes (Checkley, Jr. et al., 2009; Munday et al., 2011b), with unclear impacts on fitness. Energy costs in epithelia or calcification compartments may be enhanced by elevated pCO_2 causing a stimulation of metabolism (Section 6.3.2.1). In some cases, this may indicate imbalances in energy budget rather than increased CO_2 resistance, for example, if costs are down-regulated in muscle or liver. Enhanced calcification can then occur at the expense of growth (*medium confidence*; Wood et al., 2008; Beniash et al., 2010; Thomsen and Melzner, 2010; Parker et al., 2011).

Studies on calcifying zooplankton focused on pteropods (planktonic mollusks with aragonite shells). These form an integral part of the food web, both as grazers and prey, for example, for pink salmon (Armstrong et al., 2005; Hunt et al., 2008). In the Sub-Arctic, the Arctic, and the Southern Ocean, pteropods will reduce calcification in response to OA until at least the end of the century (*medium confidence*; Orr et al., 2005; Comeau et al., 2009; Lischka et al., 2011).

Elevated CO_2 causes behavioral disturbances in fishes (studied mostly in larvae and juveniles; Munday et al., 2010; Ferrari et al., 2011; Domenici et al., 2012; Jutfeld et al., 2013) through neural mechanisms (Nilsson et al., 2012). The long-term persistence and evolutionary relevance of these behavioral effects need further study before general conclusions can be drawn (*low confidence*; Wittmann and Pörtner, 2013; see also Table 6-3).

6.3.2.4.1. Animal life cycles

It is generally held that organisms at early life stages are always more sensitive to environmental stress than adults. In the context of ocean acidification this statement is supported by findings like larval oyster fatalities in aquaculture caused by upwelled CO_2-rich waters (*high confidence*; Barton et al., 2012). A key aspect may also be that larvae growing or developing more slowly under elevated CO_2 as in various groups including fishes (Baumann et al., 2012; see also Section 6.3.2.1) may encounter enhanced mortalities due to prolonged predator exposure. Comparative studies of animal sensitivities to OA over a complete life cycle or during critical transition phases (e.g., fertilization, egg development and hatching, metamorphosis, molting) are scarce and do not support generalized conclusions (*low confidence*).

Effects of elevated CO_2 on one life stage or transition phase may affect or carry over to the next one. Molting success into the final larval stage was reduced in a crab species (Walther et al., 2010). In a sea urchin species, negative impact was found to accumulate during 4 months acclimation of adults reducing reproductive success. This impact was, however, compensated for during extended acclimation of female urchins for 16 months (Dupont et al., 2013). Negative impact was still transferred from urchin larvae to juveniles under elevated pCO_2. Conversely, adult oysters acclimated to high CO_2 acquired resistance which was carried over to their offspring (Parker et al., 2012). More long-term acclimation studies to realistic emission scenarios are needed for generalized conclusions. Furthermore, the preposition that juvenile life stages are always more sensitive than adults needs thorough re-investigation in the context of ocean acidification, especially in the context of the notion that larvae may provide a selection pool for survival of the most suitable phenotypes (*low confidence*; Section 6.3.2.1).

6.3.2.4.2. Warm- and cold-water coral communities

In warm-water reef-building corals, OA causes genus-specific reductions in calcification (Leclercq et al., 2002; Langdon and Atkinson, 2005; Kleypas and Langdon, 2006). Nutrient availability to symbionts may sustain calcification. Heterotrophic feeding by the corals also supports energy-dependent calcification and acid-base regulation, and thus resilience (Edmunds, 2011; Figure 6-10). Females may sacrifice calcification more than males due to energetic trade-offs with reproduction (Holcomb et al., 2012). Warm-water corals are thus sensitive to future OA (*high confidence*; Table 6-3).

The cold-water coral *Lophelia pertusa* shows resilience to ocean acidification. In short-term ship-board incubations pH reductions between 0.15 and 0.3 units (540 and 790 µatm) led to calcification rates reduced by 30 to 56% (Maier et al., 2009), especially in young, fast growing polyps. However, net calcification was maintained at seawater aragonite saturation <1. Exposure to a pCO_2-induced pH reduction by 0.1 units or even to the projected end of century pCO_2 of 930 µatm led to calcification rates being maintained over 6 to 9 months (Form and Riebesell, 2012; Maier et al., 2013). This ability is probably due to a regulated upward shift of pH and carbonate saturation at organismal calcification sites (McCulloch et al., 2012; see also Figure 6-10). Natural distribution of other cold-water species covers wide natural pH gradients in Chilean fjords (*Desmophyllum dianthus*; Jantzen et al., 2013) and ranges into waters with undersaturated carbonates as in Australian waters (four scleractinian corals; Thresher et al., 2011). Pre-adaption to elevated pCO_2 apparently exists; however, species vulnerabilities to further increases in pCO_2 have not been investigated. Again, vulnerability is species specific, colonial scleractinians may be limited to water saturated or near-saturated with aragonite, whereas others are not (Thresher et al., 2011). Conclusions on the relative vulnerability of the group appear premature (Table 6-3). To what extent a further lowering of carbonate saturation values will influence the future distribution of various calcite or aragonite forming cold-water corals is not clear (*low confidence*; Guinotte et al., 2006).

6.3.2.5. Ecosystems

For insight into ecosystem level processes, laboratory studies have been supplemented with experimental studies in large volume mesocosms (i.e., >1000 L) and in the field, and with long-term field observations. Together they inform the debate over the attribution of field observations to ocean acidification.

6.3.2.5.1. Evidence from field observations

Contributions of anthropogenic ocean acidification to climate-induced alterations in the field have rarely been established and are limited to observations in individual species (see also Section 30.5.1.1.3). Shell thinning in modern planktonic foraminifera (collected 1997–2004) in the Southern Ocean compared to those from the Holocene and before was attributed to anthropogenic ocean acidification (Moy et al., 2009). Both anthropogenic OA and the upwelling of CO_2-rich deep waters (Section 30.5.4.1.4) were held responsible for shell thinning in planktonic foraminifera in the Arabian Sea over the last century (de Moel et al., 2009) or in live pteropods collected in 2008 in the Southern Ocean (*medium evidence*, *medium agreement*; Bednaršek et al., 2012). However, no changes were observed in a 57-year record of the composition and abundance of calcifying zooplankton in the increasingly acidified California Current System (Ohman et al., 2009). Possible explanations for the absence of significant responses in some studies include insufficient lengths of time series (Section 6.1.2), organisms being pre-adapted to naturally high CO_2 in upwelling or other systems, linked to a low signal-to-noise ratio, or the difficulty of detecting small OA effects in comparison with larger ecosystem effects of other drivers such as temperature, for example, in calcifying plankton (Beaugrand et al., 2013). Similarly, declines in coral calcification and performance in the field (De'ath et al., 2009) were attributed to thermal extremes, but may also include an as-yet unclear contribution from OA.

6.3.2.5.2. Microbial communities and nutrient cycles

Laboratory experiments, coastal mesocosm studies (Weinbauer et al., 2011), and field experiments (Beman et al., 2011; Law et al., 2012) have yielded various, sometimes conflicting, results on the effects of CO_2 on microbial processes. From a meta-analysis of available data, Liu et al. (2010) conclude that the rates of several microbial processes will be affected by OA, some positively, others negatively. The potential of the microbial community to adapt to ocean acidification and maintain functionality, either by genetic change at the species level or through the replacement of sensitive species or groups at the community level, remains to be explored further. At the present time there is insufficient field-based evidence to conclude that elevated CO_2 will affect natural assemblages of microorganisms (*limited evidence*, *low agreement*) with the possible exception of the negative impact on calcification (Joint et al., 2011).

Experimental studies on OA effects (through reduced pH or increased CO_2) on autotrophic and heterotrophic microbial production have provided inconsistent results. Microbes are characterized by large diversity and broad environmental adaptation, and hence may respond to environmental challenges by exploiting such diversity via species replacements (Krause et al., 2012). This makes it difficult to project the findings of laboratory experiments investigating the response of microbes to OA to the ecosystem level. Relevant variables include cellular elemental stoichiometry (C:N:P ratios; Riebesell, 2004; Fu et al., 2007), rates of CO_2 and N_2 fixation (Riebesell, 2004; Hutchins et al., 2007, 2009), rates of nitrification (Beman et al., 2011), changes in the proportion of dissolved organic carbon (i.e., DOC) to particulate photosynthate produced during carbon fixation (Kim et al., 2011), and the response of viruses (Danovaro et al., 2011).

Field experiments led to the projection that nitrification rates (ammonia oxidation to nitrite and nitrite oxidation to nitrate) of bacteria and archaea will be reduced by 3 to 44% when pH is reduced by 0.05 to 0.14 (Beman et al., 2011), corresponding to a mean rise in CO_2 by approximately 100 µatm. The reported decrease in nitrification occurred regardless of natural pH variability, providing no evidence for acclimation of the nitrifiers to reduced pH, for example, in upwelling areas. Potential changes in microbial cell abundance, possibly as a result of lower cellular nitrification rates, could further decrease the total rate of nitrification.

It remains unclear whether OA has contributed to the systematic changes in phytoplankton abundance and community structure observed over recent decades, which have largely been attributed to warming (Chavez et al., 2011). In natural assemblages from coastal and polar waters, NPP is stimulated by increased CO_2 (*medium confidence*; Riebesell et al., 2008; Tortell et al., 2008). Small differences in CO_2 sensitivity may lead to pronounced shifts in the dominance of species (Tortell et al., 2008; Beaufort et al., 2011). Quantification of the calcite mass of the coccolithophore community in the present ocean and over the last 40 kyr were in large part attributed to shifts between differently calcified species and morphotypes according to carbonate chemistry (Beaufort et al., 2011). The same study, however, also observed heavily calcified *Emiliania huxleyi* morphotypes in upwelling systems characterized by low pH, a finding which highlights the complexity of assemblage-level responses and may indicate pre-adaptation to elevated pCO_2. Owing to the complex response patterns, it is not possible to project ecosystem-level effects from effects on coccolithophore calcification in monospecific culture experiments (*low confidence*). Projections of OA impacts on phytoplankton become even more complicated by synergistic interactions with other drivers (Boyd, 2011; see also Section 6.3.5).

6.3.2.5.3. Macrophytes and macrofauna

Macrofauna and macrophyte communities have been studied in mesocosms and in ecosystems exposed to shifted upwelling regimes or at natural volcanic CO_2 vents (Fabricius et al., 2011; Kroeker et al., 2011). The latter are considered as natural analogs of future ocean acidification. An 8-year trend of (variable) pH decline in upwelled waters along the Northeast Pacific coast was paralleled by shifts in community composition, where shelled species like mussels were replaced by fleshy algae and barnacles (Wootton et al., 2008). Macrofaunal calcifiers at CO_2 vents (Hall-Spencer et al., 2008; Fabricius et al., 2011) and in mesocoms (Christen et al., 2013) display a lowering of species richness. These findings suggest that non-calcifiers increasingly outcompete calcifiers once pH_T decreases to a mean of 7.8 to 7.7 (*medium confidence*). Finally, a loss of calcifiers from mesocosms occurred around 0.5 units below the pH values expected from OA under RCP8.5 by 2100 (*medium confidence*; Christen et al., 2013). At CO_2 seeps, calcitic bryozoans replace coralline algae, which have more soluble high-calcite skeletons (Martin et al., 2008). Seagrasses and non-calcifying algae gain a competitive advantage (Fabricius et al., 2011). Coral communities exposed to high pCO_2 waters (from upwelling or seeps) have lower growth, calcification, and biodiversity (Manzello et al., 2008; Fabricius et al., 2011), resulting in a shift from net accretion to erosion (Box CC-CR). The use of seeps as analogs of future OA is limited as pH variability is high at these sites, such that effective values may be lower than indicated by the average change (Hall-Spencer et al., 2008; Porzio et al., 2011). During periods of high pH at the seeps, they are recolonized by invertebrates and fishes from neighboring areas with normal pH, compromising assessments of long-term sensitivity thresholds. Overall, findings available from mesocosms and natural analogs indicate losses in diversity, biomass, and trophic complexity of benthic marine communities due to elevated CO_2 (*high confidence*) and support the projection of similar shifts in other systems with continued OA (*medium confidence*).

Enhanced freshwater input by poorly buffered rivers or by precipitation, into estuaries, brackish oceans like the Baltic (Section 30.5.3.1.4), and into freshening polar oceans, reduces salinity and alkalinity at rising atmospheric pCO_2 and thereby, alters the carbonate system and enhances OA (Section 6.1.1). Estuaries usually have OMZs, where background pCO_2 is elevated. Its reduction by dilution causes the acidification effect to be somewhat less. Enhanced pH reduction and variability in hyposaline waters may constrain the distribution of sensitive species further (*low confidence*; Miller et al., 2009; Denman et al., 2011).

6.3.2.5.4. Conclusions

Natural analogs and laboratory and mesocosm experiments provide evidence for differential effects of ocean acidification on species and communities. Sensitivity to OA is species specific (*high confidence*); differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (*low* to *medium confidence*). OA may stimulate global net primary production (*low confidence*) and nitrogen fixation (*medium confidence*). OA will increase the abundance and primary production of non-calcifying macrophytes, but will be harmful to calcifying algae and many heterotrophs (*medium confidence*). Ecosystems relying on calcified structures and at risk of dissolution under OA include warm-water coral reefs (*high confidence*) and their cold-water equivalent (*medium confidence*). Further studies need to explore how OA may change the composition of communities, impact food webs, and affect higher trophic levels.

6.3.3. Life in Hypoxia and Anoxia

6.3.3.1. Principles

Hypoxia constrains organisms which rely on aerobic metabolism (Section 6.1.1; FAQ 6.2). Below O_2 concentrations of 60 µmol kg^{-1}, commonly termed hypoxic (Section 6.1.1.3), communities undergo species losses and replacements and are transformed into communities with species showing characteristic hypoxia adaptations. However, O_2 can limit animal life at even higher levels, just below air saturation (Gilly et al., 2013). Organisms' tolerance thresholds have been defined by either the critical O_2 partial pressure (P_c) or concentration (O_2crit). Thresholds vary across domains and are highest for large multicellular organisms. Among these, the P_c at rest varies depending on species, body size, and life stage. In animals below the P_c aerobic metabolic rate fails to be maintained and anaerobic metabolism contributes to energy production (Pörtner and Grieshaber, 1993). The critical oxygen threshold is set by the capacity of ventilatory and circulatory systems to supply O_2 and cover demand. The threshold increases once metabolism is stimulated by muscular activity, temperature, or food uptake (Pörtner, 2002a; Ekau et al., 2010; Seibel, 2011; see also Figure 6-11). At extreme temperatures, O_2crit approaches the oxygen content of air-saturated water (Pörtner, 2010; McBryan et al., 2013), indicating high sensitivity to hypoxia in the warmth. Most animals can only sustain anaerobic metabolism temporarily, even if they are energy efficient and survive long periods of anoxia (Grieshaber et al., 1994). Such time-limited tolerance is higher in large than in small individuals or larvae, related to the higher capacity of anaerobic metabolism in large specimens (Gray et al., 2002; Jessen et al., 2009).

6.3.3.2. Microbes

Bacteria and protists consume ambient oxygen down to very low levels in oxygen minimum zones and sustain OMZs by their metabolic diversity (Figure 6-11; WGI AR5 Section 3.8.3). OMZs form habitat for both anaerobic and aerobic microbes that can utilize very low (<1 µmol kg^{-1}) O_2 concentrations (Stolper et al., 2010). Hypoxia is paralleled by elevated pCO_2 and enhanced acidification. Expanding OMZs will select for the proliferation of spezialized microbes (*high confidence*).

6.3.3.3. Animals and Plants

In mesopelagic OMZs, zooplankton also contribute to the development of hypoxia (Robinson et al., 2010; see also FAQ 6.2). During daytime zooplankton congregate at the upper margin of OMZs, where the degradation of organic material causes intensified respiration and oxygen depletion (Bianchi et al., 2013). Animals living permanently in the OMZ still cover virtually all energy demand by aerobic metabolism. This requires special adaptations leading to a reduction in O_2 and energy demand, and the improved ability to use available O_2 efficiently. Enhanced hypoxia tolerance reflected in low O_2crit values is supported by small body size and by cold temperature (Vetter et al., 1994; Pörtner, 2002b; Levin et al., 2009). Accordingly, low O_2 levels support abundant meiofauna (very small fauna, <1 mm) that benefit from abundant food and reduced predation by larger organisms (Levin, 2003). Under suboxia only specialists can survive (Vaquer-Sunyer and Duarte, 2008). Expansion of suboxic and anoxic centres of pelagic OMZs and benthic dead zones will lead to loss of habitat for animal life (*high confidence*).

Large, more active animals such as fishes, crustaceans, and muscular (as opposed to ammoniacal) squids tend to have high O_2 demands associated with high O_2crit thresholds, and are therefore excluded from permanently hypoxic water bodies. However, even in high-activity animal groups some specialists such as Humboldt squid or bigeye tuna have adapted to enter hypoxic environments though only temporarily (Richards et al., 2009; Seibel, 2011). The time-limited tolerance of animals to hypoxia below the O_2crit is maximized by the depression of energy demand, for example, during periods of metabolic arrest (e.g., developmental arrest or diapause of copepods; Auel et al., 2005). Hypoxia-adapted lifeforms will benefit from expanding OMZs (*high confidence*).

There is little information on the hypoxia sensitivity of macrophytes or their O_2crit values. In eelgrass (*Zostera marina*), warming causes the hypoxia threshold to rise due to a strong increase in tissue respiration. Concomitant water or sediment hypoxia can elicit tissue anoxia and sudden die-offs (Raun and Borum, 2013). By contrast, macroalgae attached to rocks rarely encounter anoxia (Raven and Scrimgeour, 1997). Expanding benthic OMZs will constrain the distribution of macrophytes (*medium confidence*).

6.3.3.4. Ecosystems

OMZs, shoaling, and expanding vertically and laterally (Gilly et al., 2013) will cause habitat and abundance losses for intolerant taxa such as mesopelagic (Koslow et al., 2011) and epipelagic fishes with a high O_2 demand (*medium confidence*; Prince et al., 2010; Stramma et al., 2012; see also FAQ 6.2). In line with the distribution of hypoxia sensitivities (Figure 6-11; Sections 6.3.3.1, 6.3.3.3), expanding OMZs will further constrain the distribution of key zooplankton and nekton species and influence their diurnal and ontogenetic vertical migrations (*medium confidence*; Ekau et al., 2010). The composition of microbial and faunal pelagic communities will shift from diverse mid-water assemblages to migrant biota that return to oxygenated surface waters at night (Seibel, 2011). Dissolved O_2, among other factors, plays an important role in shaping large alternating fluctuations of sardine and anchovy abundances, particularly off Peru. Anchovies are not strongly affected by a shallow oxycline (<10 m), while sardines actively avoid such conditions (Bertrand et al., 2010). Where OMZs intersect the continental shelves, groundfishes (McClatchie et al., 2010) and large benthic invertebrates such as crabs display high mortalities (Chan et al., 2008). Susceptibility of early life stages to hypoxia in both pelagic and benthic ecosystems

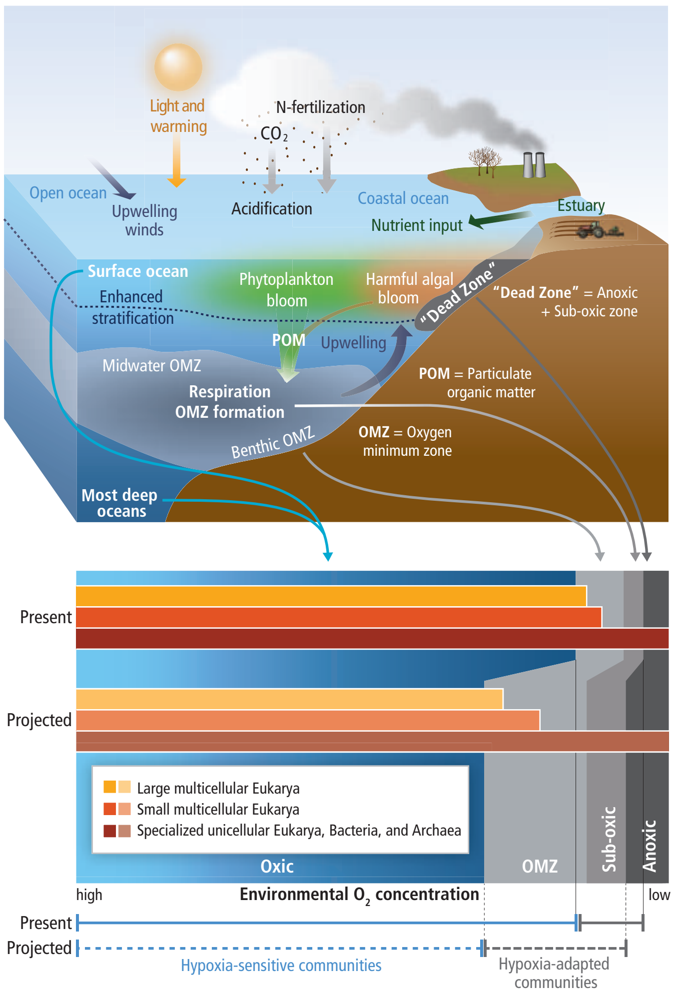


Figure 6-11 | (a) Principal mechanisms underlying the formation of hypoxic conditions and their biological background (modified from Levin et al., 2009; Levin and Sibuet, 2012). The buoyancy flux from fluvial discharges produces sharp density stratification at the base of the freshened layer (also valid for ice melt and high precipitation) near the surface and, hence, vertical mixing is greatly reduced. In consequence, the nutrient inputs from the river and the atmosphere accumulate in a narrow upper layer, leading to blooms of phytoplankton, possibly including harmful algae. The enhancement of oxygen consumption due to aerobic decomposition of sinking particulate organic matter (POM) results in hypoxic conditions of benthic and mid-water oxygen minimum zones (OMZs). Enrichment of nutrients (eutrophication) results in coastal dead zones. In the open oceans, heating of the upper layer increases stratification, while the wind-driven upwelling of hypoxic, nutrient-rich water from deeper layers adds to the formation of the OMZs (Box CC-UP). (b) Distribution of free-living marine organisms (microbes such as archaea, bacteria, protists, small and large multicellular animals, and plants) across the ranges of O_2 concentrations in various water layers. Hypoxia tolerance is enhanced in small compared to large organisms, allowing unicellular species and small animals to thrive in extremely hypoxic habitats. Species richness and body size of animals decrease with falling O_2 levels.

(Ekau et al., 2010) threatens population survival. Effects of hypoxia propagate along the food chain, constraining fish stocks and top predators (*high confidence*; Stramma et al., 2010). Hypoxia reduces biodiversity (Levin et al., 2009; Gooday et al., 2010) and causes the marginalization of calcifiers, due to low metabolic rates and high pCO_2 (*high confidence*; Levin, 2003; Levin et al., 2009).

The expansion and enhanced variability of OMZs increases dissimilatory nitrate reduction and anaerobic ammonium oxidation (anammox), both releasing N_2 into the atmosphere, reducing the availability of fixed nitrogen, and limiting oceanic primary productivity (*medium confidence*). Water column denitrification and N_2 fixation are spatially and temporally variable (*limited evidence*, *low confidence*), suggesting that climate effects on these processes are unlikely to operate uniformly (Brandes et al., 2007; Fernandez et al., 2011; Franz et al., 2012).

If O_2 levels decline and OMZs expand, tolerant taxa, such as anaerobic bacteria (Ulloa et al., 2012), gelatinous zooplankton (medusae, ctenophores), selected fishes (gobies, hake), and possibly selected cephalopods (Gilly et al., 2006; Bazzino et al., 2010) will respond with range expansions or population growth. Similar phenomena are expected with intensified upwelling causing extensive mortalities of coastal fishes and invertebrates (Box CC-UP). A community change toward hypoxia-tolerant fauna will occur in mid-water (*high confidence*). The diversity of macroorganisms will decrease and, finally, higher marine organisms will disappear and heterotrophic microorganisms will dominate (*high confidence*). In isolated water bodies such as the Black Sea, warming will lead to the expansion of anoxia and hydrogen sulphide (H_2S) poisoning, reduce pelagic and bottom faunal distributions, and shape trophic relations, energy flows, and productivity (Daskalov, 2003; Fashchuk, 2011).

6.3.4. Mixed Layer Depth and Light Shaping Net Primary Production

The upper ocean is characterized by physical and chemical gradients in the surface mixed layer that influence the magnitude of photosynthetic carbon fixation, often termed net primary production (NPP). The availability of light and nutrients to photoautotrophs sets daily rates of NPP and may be altered directly or indirectly, through changing mixed layer depths, shifts in the circulation regime at different spatial scales, and the physical displacement of organisms (Section 6.1.1.4; Box CC-PP; Figure 6-2). A changing climate will affect mixed layer depth, cloudiness, and/or sea ice areal extent and thickness and thereby modulate NPP (*high confidence*). A stronger vertical density gradient will reduce the communication between the sunlit upper ocean where photosynthesis takes place and the underlying nutrient-rich waters (Figure 6-2). The supplies of plant nutrients (macro-nutrients) such as nitrate, and of micro-nutrients such as iron (Pitchford and Brindley, 1999) vary seasonally (Boyd, 2002) and regionally (Moore et al., 2002), such that NPP may be simultaneously limited (co-limited) by more than one resource (Saito et al., 2008; see also Section 6.3.5).

The changing range and intensity of underwater light will lead to changes in NPP as well as in phytoplankton community composition (Doney, 2006; Boyd et al., 2010). The response of phytoplankton to changing sunlight involves photo-physiological acclimation via changes in cellular chlorophyll, but such acclimation is constrained by unidentified limits (Falkowski and Raven, 1997). A longer growing season, with more sea ice-free days between 1998 and 2009, may have increased NPP in open Arctic waters (Arrigo and van Dijken, 2011; see also Box CC-PP), complemented by massive under-ice blooms as seen in 2011, favored by light that penetrates surface melt ponds and thinner, for example, first-year ice (Arrigo et al., 2012). There are also reports of increased incidences of high phytoplankton stocks, and hence of greater NPP, deeper in the water column (i.e., where it cannot be detected by satellite) during summer in the Arctic, which have implications to assessing changes in NPP from space (Hill et al., 2013). Little is known about shifts from sea ice algae to free-drifting phytoplankton expected with a decrease in sea ice cover and effects of increased light in polar waters in the coming decades (*low confidence*). In the Arctic, summer ice melt led to a rapid export of sea-ice algae to the deep ocean (Boetius et al., 2013). As some krill feed primarily on sea ice algae, it is unclear (*low confidence*) whether they will adapt to feeding mainly on free-drifting phytoplankton (Smetacek and Nichol, 2005).

A range of time series observations, from *in situ* phytoplankton abundances to satellite remote sensing, have been used to assess whether phytoplankton stocks and hence rates of NPP have altered over recent decades. Increases in phytoplankton stocks were found in regions where colder waters had warmed in the Northeast Atlantic, whereas the opposite trend was observed for warm-water regions from a phytoplankton abundance time series (Richardson and Schoeman, 2004). Lower chlorophyll concentrations at warmer SSTs in nutrient-poor low-latitude waters, based on satellite ocean color data, have been interpreted as an effect of increased stratification on phytoplankton stocks. It has thus been suggested that expanding, permanently stratified, low-chlorophyll, tropical regions (WGI AR5 Chapter 3) indicate declining phytoplankton stocks in the warming oligotrophic waters of the North and South Pacific and North and South Atlantic (*limited evidence*, *low agreement* due to methodological uncertainties; Box CC-PP; Polovina et al., 2008; Signorini and McClain, 2012; see also Section 30.5.1.1.2). Furthermore, a transition to conditions favoring increased frequency or even permanence of El Niño in a warmer future (Wara et al., 2005) and further expansion of subtropical ocean gyres (Polovina et al., 2008; see also Section 30.5.6) may lead to lower global ocean NPP (*low* to *medium confidence*).

However, these long-term "blended" projections (i.e., constructing a biomass time series using multiple proxies such as ocean transparency) of a global decrease in phytoplankton biomass (Boyce et al., 2010) have been refuted (Mackas, 2011; McQuatters-Gollop et al., 2011; Rykaczewski and Dunne, 2011). Time series shorter than 20 years do not resolve impacts of bi-decadal variation such as the Pacific Decadal Oscillation or the lunar nodal cycle (e.g., Watanabe et al., 2008; Henson et al., 2010). Analysis of continental shelf ecosystems, including field data in the most productive upwelling areas covering the last 20 years (e.g., Chavez et al., 2011), revealed a large variety of trends at scales of several decades but a general increase in NPP on most shelves (Sherman and Hempel, 2009; Bode et al., 2011), possibly caused by natural climate variability, anthropogenic climate change, and/or anthropogenic eutrophication. Recent field measurements document increasing quantities of both anthropogenic fixed N (Duce et al., 2008) and biologically fixed atmospheric nitrogen (Mouriño-Carballido et al., 2011) entering the open ocean, which could lead to increased NPP especially in warm, stratified tropical and subtropical oceans provided sufficient phosphate and other growth requirements are present (*low confidence*; e.g., Sohm et al., 2011).

For heterotrophs, from bacteria to fish, mammals, and birds, the uptake of organic material as food, ultimately provided by NPP, is central not only to productivity but also for fueling energy-consuming functions including the resistance of organisms to environmental change and pathogens (Sections 6.3.1-2). Any direct influence of climate on the abundance and quality of feed organisms will thus translate to indirect effects on the productivity and well-being of foraging animals (*high confidence*; Figures 6-5a, 6-7a, 6-12).

Overall, pelagic systems respond to climate change by region-specific changes in productivity with the projection of a small net reduction in global ocean NPP by 2100 (*medium confidence*; Box CC-PP). The spatial reorganization of NPP between latitudes affects higher trophic levels by alteration of the composition and functioning of pelagic communities (*medium confidence*).

6.3.5. Concurrent Responses to Multiple Drivers

Climate change alters oceanic properties globally, with concurrent changes in temperature, dissolved CO_2 and O_2, light, and nutrient concentrations (e.g., Sarmiento et al., 1998; Matear and Hirst, 1999; Boyd and Doney, 2002; Ekau et al., 2010; see also Figure 6-2). Additional direct human interventions at regional scale comprise the introduction of non-native species, overfishing, pollution, long-range atmospheric transport of nitrogen, point-source eutrophication, and habitat destruction (Carlton, 2000; Boyd and Hutchins, 2012). Worldwide alterations in marine ecosystems (Pauly et al., 1998; Österblom et al., 2007) have been linked to direct human activities, especially fishing (Frank et al., 2005; deYoung et al., 2008; Casini et al., 2009), but may also be caused to some extent by climate variability and change (Cheung et al., 2013a).

Alteration of each individual property has pronounced effects on organisms from microbes to animals, and hence on ecosystems (Sections 6.3.1-4). The cumulative effects of these factors will result in complex patterns of change, from organismal physiology to the areal extent and boundaries of biogeographic regions (Table 6-4). In many organisms, effects of ocean acidification interact with those of other key drivers such as temperature and hypoxia (Boyd, 2011; Gruber, 2011; Pörtner, 2012) and translate from molecular to ecosystem level impacts. In phytoplankton, low light (Zondervan et al., 2002) or nitrogen limitation (Sciandra et al., 2003) limit beneficial OA effects on photosynthesis and have a strong negative effect on plankton calcification (Rokitta and Rost, 2012). Nutrients and light support functional adjustments to OA through gene expression changes (Dyhrman et al., 2006; Richier et al., 2009).

Similar to today, paleo-events such as the Palaeocene-Eocene Boundary demonstrate concurrent warming, enhanced stratification of the oceans, deoxygenation of deeper waters, and OA, albeit at a rate more than 10 times slower than today's rate (Section 6.1.2). Both the complexity of paleo-ecosystem changes and the complexity of present effects confound the clear attribution of biological trends to individual drivers (Parmesan et al., 2011). For warming and hypoxia, changes are accelerated by effects of shifting seasonal or even diurnal extremes and their frequency on organisms and ecosystems (*medium evidence*, *medium agreement*) (e.g., Pörtner and Knust, 2007; Díaz and Rosenberg, 2008). This may also apply to effects of anthropogenic OA (*limited evidence*, *low agreement*).

6.3.5.1. Principles

Effects of various climate drivers on ocean ecosystems are intertwined and effects may be exacerbated by responses of biota. For example, warming reduces O_2 solubility and enhances biotic O_2 demand, which exacerbates hypoxia, produces CO_2, and causes acidification (Millero, 1995; Brewer and Peltzer, 2009). Drivers act with either additive, synergistic (i.e., amplification of) or antagonistic (i.e., diminution of) effects. A meta-analysis of 171 experimental studies that exposed marine systems to two or more drivers identified cumulative effects that were additive (26%), synergistic (36%), or antagonistic (38%) (Crain et al., 2008). Effects range from direct impacts of ocean warming on organismal physiology (Pörtner and Knust, 2007) to ocean acidification acting together with warming, for example, on coccolithophore calcite production and abundances (Feng et al., 2009), or with hypoxia and/or salinity changes (Table 6-4). Interactions of predominantly temperature, ocean acidification, and hypoxia have *likely* been involved in climate-driven evolutionary crises during Earth history (Pörtner et al., 2005; see also Section 6.1.2).

Effects on individual organisms may also reflect intertwined impacts of ocean warming, acidification, and hypoxia, which may operate through interrelated functional principles (Pörtner, 2012). Such knowledge helps to reconcile apparently contrasting findings. For example, warming toward the thermal optimum (Figure 6-5a) stimulates resistance to OA; CO_2-induced disturbances of growth and calcification were reversed by concomitant warming (Findlay et al., 2010; Sheppard-Brennand et al., 2010; Walther et al., 2011). Warming to above optimum temperatures, however, constrains performance and exacerbates sensitivity to hypoxia and/or elevated CO_2 (Figure 6-5, e.g., via decreased calcification; Rodolfo-Metalpa et al., 2011). Both hypoxia and/or elevated CO_2 in turn enhance heat sensitivity, as seen for CO_2 in crustaceans (via decreased heat limits: Walther et al., 2009; Findlay et al., 2010), coral reef fishes (via reduced performance: Munday et al., 2009b), and corals (via decreased calcification and CO_2-enhanced bleaching: Reynaud et al., 2003; Anthony et al., 2008). This translates into a narrowing of the thermal niche (Walther et al., 2009; see also Figure 6-5), which will shrink biogeographic ranges, affect species interactions, and shift phenologies (Figure 6-7a). Hence, extreme warming and hypoxia exacerbate CO_2 effects and vice versa (*medium confidence*). Such principles need to be reconfirmed across organism taxa (Pörtner, 2012).

Differences in organism adaptation to a climate zone's characteristic temperatures, temperature variability, oxygen content, and ocean chemistry may shape vulnerability to climate change. In high polar species evolutionary cold adaptation enhances vulnerability to warming

Table 6-4 | Potential interactions between modes of anthropogenic forcing (environmental; foodwebs; harvesting) on different levels of biological organisation. These interactions, from simple to complex, are illustrated with examples from the published literature. Unknown denotes no published information is available for each of these categories. NA denotes not applicable for this category.

Biological organization studied at ecosystem level	Anthropogenic forcing			
	Single environmental driver	Multiple environmental drivers	Fishing/foodwebs	Fishing/climate change
Individuals	Lab experiments and field observations show that warming alters organismal physiology and thereby growth (Pörtner and Knust, 2007).	Shipboard manipulation experiment addressing interactive effects of temperature and CO_2 on coccolithophore calcification (Feng et al., 2009).	NA	Unknown
Population	Physiological effects of warming change population abundance *in situ* (Pörtner and Knust, 2007). Lab cultures show how altered pH elicits different responses of coccolithophore species (Langer et al., 2006).	Lab cultures show differential responses of cyanobacterial groups to temperature and CO_2 (Fu et al., 2007).	Altered maturation age and growth rate of populations due to fishing (Fairweather et al., 2006; Hseih et al., 2006).	Interactive effects on cod populations of fishing and alteration of salinity (Lindegren et al., 2010).
Ecosystem	Mesocosm experiments simulating the effect of individual drivers (e.g., ocean acidification effects on benthos: Christen et al., 2013; and on pelagic communities: Riebesell et al., 2013).	Mesocosm experiments studying differential effects of light and temperature, on copepods versus diatoms (Lewandowska and Sommer, 2010).	Effects of fishing on ecosystem structure — trophic cascades (Frank et al., 2005).	Interplay of fishing and climate pressures on ecosystems promotes lower trophic levels (Kirby et al., 2009); enhances diversity loss in benthic communities (Griffith et al., 2011).
Biome	Time series observations on warming and geographical shifts of zooplankton biomes (Beaugrand et al., 2009).	Unknown	Unknown	Unknown

Approaches: = Experiments (lab or field) = Observations = Modeling = Not applied (*medium confidence*). In OMZs, marine sediments, and in polar waters (due to high solubility in the cold), CO_2 levels are elevated and adaptation may reduce sensitivity and reliance on calcified structures (Clark et al., 2009; Walther et al., 2011; Maas et al., 2012). The observed shift from "overcalcified" to "weakly calcified" coccolithophores *Emiliania huxleyi* in cold waters may reflect a related shift in ecotype dominance (*limited evidence*, *medium agreement*; Cubillos et al., 2007).

Despite such potential adaptation, polar calcifiers exposed to higher CO_2 and lower carbonate saturation levels have been hypothesized to be highly sensitive to further CO_2 accumulation (*limited evidence*, *high agreement*; Orr et al., 2005). Here it appears relevant that cold temperature reduces energy demand and thereby lowers resistance to ocean acidification. Both energy demand and resistance are higher in eurytherms than in high polar and deep sea stenotherms (*limited evidence*, *medium agreement*; Pörtner, 2006; e.g., crustaceans: Pane and Barry, 2007: cf. Whiteley, 2011). In turn, tropical species may be more sensitive than temperate zone species (Pörtner et al., 2011). This rough differentiation of sensitivity is complicated by the local adaptation of populations from within-species genetic variability (*low confidence*).

Temperature influences hypoxia sensitivity (Section 6.3.3). Warming causes the minimum tolerated O_2 level to rise, enhancing vulnerability (*high confidence*). Conversely, hypoxia enhances vulnerability to warming in animals. This may occur fastest in warm oceans, where metabolic rates are higher and animals live closer to upper thermal limits (*medium confidence*; Pörtner, 2010). However, evolutionary adaptation has led to high hypoxia tolerance (low P_c or O_2crit values) in some warm-adapted coral reef fishes. Further warming then causes a rise in P_c which cannot be compensated for (Nilsson et al., 2010). Limits to hypoxia adaptation coincide with upper thermal limits (*medium confidence*).

Complexity in responses rises with the number of drivers involved. Enhanced river runoff and increased precipitation cause a shift from marine to more brackish and even freshwater communities, with unclear consequences for effects of other drivers. Falling primary production reduces resilience of higher trophic levels (Kirby and Beaugrand, 2009; Stock et al., 2011). The introduction of non-indigenous species, when supported by climate-induced shifts in interactions, may promote the displacement of ecotypes and shifts in ecosystem functioning, for example, in the Mediterranean Sea (Occhipinti-Ambrogi, 2007; Coll et al., 2010).

6.3.5.2. Microbes

Both synergistic and antagonistic effects of multiple drivers on microbial biota in the surface ocean have been observed in manipulation or modeling experiments (Folt et al., 1999; Boyd et al., 2010; Gruber, 2011). The productivity of many microbes was simultaneously limited by, for example, availability of nitrate and phosphate, cobalt and iron (Saito et al., 2002; Bertrand et al., 2007), or iron and light (Boyd et al., 2010; see also Section 6.2.2). Warming and high CO_2 synergistically enhanced photo-physiological rates of the cyanobacterium *Synechococcus*, whereas the cyanobacterial group *Prochlorococcus* showed no change (Fu et al., 2007). The magnitude of CO_2 effects on growth, fixation rates, or elemental ratios within single species is often strongly modulated by nutrient availability and light conditions (e.g., Sciandra et al., 2003; Zondervan et al., 2002; Kranz et al., 2010). Such differences cause floristic shifts in phytoplankton with the potential to restructure predator-prey interactions (Table 6-4).

Co-limiting factors vary by group, such as nitrogen fixers (e.g., Hutchins et al., 2007; Kranz et al., 2010), diatoms (Boyd et al., 2010), and coccolithophores (e.g., Feng et al., 2009; Rokitta and Rost, 2012). This limits the ability to project climate change effects (Boyd et al., 2010). The most reliable projections at ocean basin scale come from modeling, which mainly points to synergistic effects, such as those of elevated CO_2, hypoxia, and warming. For example, OA is projected to alter sinking particles (C:N ratio and/or reduced calcite content and slower sinking) with a consequent knock-on effect on water column O_2 demand already stimulated by warming, thereby causing expansion of OMZs (Gruber, 2011).

6.3.5.3. Animals and Plants

High oxygen availability alleviates thermal stress as seen in fish and mollusks (Mark et al., 2002; Pörtner et al., 2006). Conversely, hypoxia reduces heat tolerance (Section 6.3.5.1), but acclimation to hypoxia compensates for this and increases thermal tolerance (Burleson and Silva, 2011), for example, by enhancing blood pigment content or reducing energy demand. Tolerances to hypoxia and to high temperature may positively correlate in some fishes, indicating potential for adaptive evolution under climate change (*low confidence*; McBryan et al., 2013).

As a consequence of hypoxia narrowing thermal ranges (Section 6.3.5.1), combined warming and expanding hypoxia may cause mid-water mesopelagic and demersal fish stocks to decline at rates much quicker than anticipated in the California Current Ecosystem (McClatchie et al., 2010; Koslow et al., 2011). In benthic fauna, warming will also increase vulnerability to hypoxia. Experiments showed a rise in lethal oxygen concentrations by 25% and thereby reducing survival by 36% at 4°C warmer temperatures (Vaquer-Sunyer and Duarte, 2011). Hence, warming is expected to expand the area of ecosystems affected by hypoxia even if oxygen concentrations remain unchanged (*high confidence*). Under combined hypoxia and warming, CO_2 can extend short-term passive tolerance (despite constraining long-term tolerance). It facilitates a reduction in energy demand (Reipschläger et al., 1997; Pörtner et al., 2000), thereby extending survival of transient extremes of temperatures or hypoxia (*medium confidence*).

In macroalgae (non-calcifying) light availability modulates the response to elevated pCO_2 and temperature levels (Russell et al., 2011; Sarker et al., 2013). In warm-water corals, warming acting synergistically with CO_2 reduces calcification and increases sensitivity to bleaching (*high confidence*; Anthony et al., 2008). Combined warming and OA following SRES B1 (≈RCP4.5, reduced emission) and A1FI (≈RCP8.5, business-as-usual) scenarios in mesocosms caused losses of symbionts and corals, and a nocturnal decalcification of the reef community in summer. Present-day conditions already imply reduced resilience to episodic extreme events such as cyclones (Dove et al., 2013; see also Box CC-CR).

6.3.5.4. Ecosystems

The cumulative impacts of climate change drivers underlie alterations of species interactions and ecosystem structure and functioning, including changes in trophodynamics and the physical and chemical characteristics of habitats (*high confidence*). These effects combine with more indirect effects, such as shifts in stratification and productivity, expanding oxygen minimum zones, and the changing composition and biomass of food (partly resulting from direct effects on prey organisms) (*high confidence*). These complexities reduce the precision and reliability of quantitative projections (Section 6.5), including uncertainties concerning shifts in upwelling and their future role in global primary production and the development of fish stocks (Box CC-UP).

At the level of animal communities, effects of various drivers remain largely unexplored, some are highly complex. For example, the net eastward shift of Pacific skipjack tuna between 1980 and 2009 was linked to the shifting aggregation of macrozooplankton and micronekton, involving complex interactions of climate variability (due to ENSO; Section 30.5.2), warming ocean surface, shallowing mixed layer depth relative to the position of the warm pool, and the convergence of the pool with the Pacific Equatorial Divergence Province (Lehodey et al., 2011; see also Section 30.5.6.1.1). Interactive drivers will affect the relative performance of interacting species, thereby shifting species ranges, interactions, and food webs (*medium confidence*; Figure 6-7a). Adaptation to various climate zones modifies the roles of light and temperature in seasonalities and species interactions (Bradshaw and Holzapfel, 2010). Moderate hypoxia expansion in warming seas, for example, as the stratified central North Sea (Queste et al., 2013) may well influence the degree of temperature-induced species displacements (Figure 6-7b).

Impacts of climate change on benthic ecosystem engineers can also profoundly alter ecosystems. Tropical corals respond to ocean warming and acidification by increased bleaching, impeded calcification rates, and increased incidence of disease (*high confidence*; Veron et al., 2009; Veron, 2011; see also Sections 6.3.1-2, 30.5.6; Box CC-CR). In coral reefs under multiple stressors, differentiation of these large-scale phenomena into species-specific sensitivities is highly uncertain as trend data are virtually nonexistent (Brainard et al., 2011). Little is known about impacts on deep-water or cold-water corals and sponges, tropical calcified algae, bryozoans, sponges, and tube-forming serpulid worms (Wood, 1999). The reliance of all of these on surface productivity makes them vulnerable to any alteration in food supply. Projected severe stress from increased temperature, hypoxia, and ocean acidification will cause reduced performance and increasing mortality in ecosystem engineers (*high confidence*), and a deterioration of habitat characteristics for other organisms (*medium* to *low confidence*).

As a corollary, shifts in the geographical distributions of marine species (e.g., to higher latitudes or deeper waters; Figure 6-7b; Section 6.5.2) cause changes in community composition and interactions (Harley, 2011; Simpson et al., 2011; Hazen et al., 2013). Some species may gain predominance and abundance from fitness benefits (Figure 6-7) while others become less competitive or easier prey (Occhipinti-Ambrogi, 2007). Thereby, climate change will reassemble communities and affect biodiversity, with differences over time and between biomes and latitudes (*high confidence*; Parmesan and Matthews, 2005; Sala and Knowlton, 2006; Cheung et al., 2009; Parmesan et al., 2011; see also Box CC-PP; Section 6.5).

6.3.6. Food Web Consequences

Community reassembly under climate change involves a change in species composition and strongly alters food web structure, for example, causing shifts in trophic pathways (Kirby and Beaugrand, 2009; Moloney et al., 2011; see also Figure 6-12), some of which are irreversible (Jarre and Shannon, 2010). Through trophic cascades (Cury et al., 2003; Luczak et al., 2011), climate affects predation, competition, and food availability (e.g., via changes in NPP; Figure 6-12; Utne-Palm et al., 2010), including fish stocks (Parsons and Lear, 2001; Brown et al., 2010). Trophic amplification then drives an ecosystem towards a new stable structure or regime, which may be difficult to reverse (Folke et al., 2004). Warming may result in consumer control of food web structure because respiration of heterotrophic zooplankton and bacteria increases more strongly with warming than does photosynthesis of autotrophic phytoplankton (*medium confidence*; O'Connor et al., 2009).

Many impacts of climate change on food webs resemble those caused by fishing, pollution, eutrophication, and associated hypoxia (Section 6.3.3), and habitat change (Brander, 2007); unambiguous attribution to climate remains difficult (*low* to *medium confidence*; Parmesan et al., 2011). Some of these factors also affect food web responses to climate change. Fishing truncates the age and size structure of populations, making them more dependent on annual recruitment and reducing their ability to buffer environmental fluctuations (Genner et al., 2010; Planque et al., 2010; Botsford et al., 2011; see also Figure 6-12). Both adult and larval fishes show greater variability in abundance in exploited compared to unexploited populations (Hsieh et al., 2008). Warming, acidification, and removal of top or competing predators may all contribute to large fluctuations in gelatinous plankton (e.g., jellyfish) populations (*low confidence*; Molinero et al., 2005; Richardson and Gibbons, 2008; Richardson et al., 2009; Condon et al., 2012).

Analyzing impacts on key species provides insight into how individual components of a food web will respond to perturbations. However, projections of future states must include the complex food web interactions that influence the species and system-level responses, which affect stability and resilience of the overall ecosystem (Neutel et al., 2007; Dunne and Williams, 2009; Romanuk et al., 2009). There is no single approach currently available that includes the complex links within and among ecosystems, biogeochemistry, and climate as needed for projections of future states of marine food webs (Fulton, 2011; Moloney et al., 2011). In conclusion, there is *low confidence* in the quantitative projections of such changes (for further discussion see Section 6.5).

6.3.7. Marine Reptiles, Mammals, and Birds

6.3.7.1. Principles

Marine reptiles (turtles, snakes, crocodiles), mammals, and seabirds breathe air but live mostly in water; some shift or expand their ranges

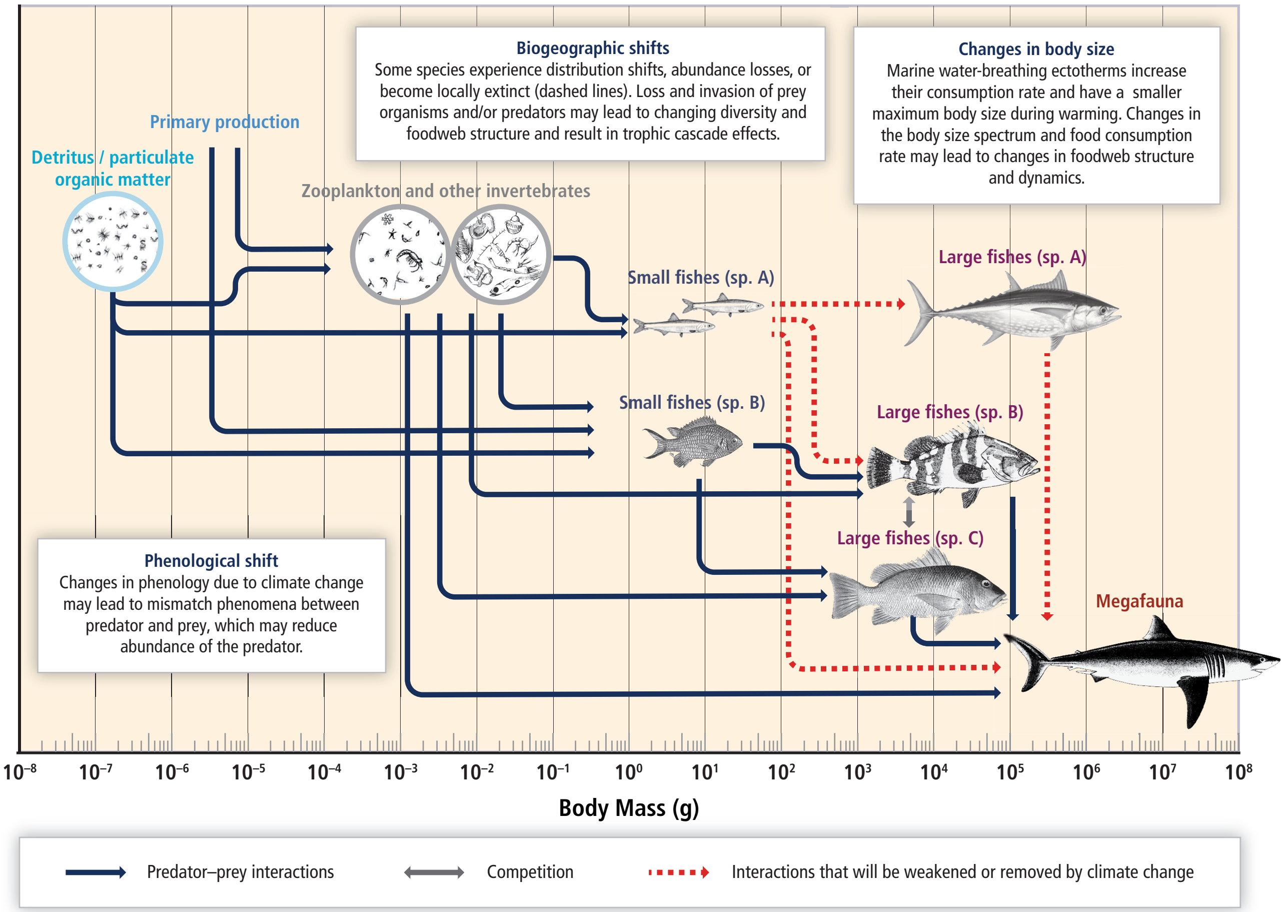


Figure 6-12 | Schematic diagram of expected responses to climate change in a marine food web. A coupled pelagic and benthic food web is structured by the body size spectrum of species. Combined warming, hypoxia, and ocean acidification reduce body size, shift biogeographies, change species composition and abundance, and reconfigure trophic linkages and interaction dynamics. Fishing generally removes large-bodied species and truncates the body-size spectrum of the community. This confounds the detection and attribution of food web responses to climate change. Arrows represent species interactions (e.g., between predator and prey or competitors for food or space). Broken lines reflect the potential loss of populations and trophic linkages due to climate change.

as a result of climate warming. The body temperature of ectothermic reptiles is set by ambient conditions; only at large body size may their body store heat and its temperature be higher than ambient. Reptiles are thus more responsive to temperature than homeothermic seabirds and marine mammals (McMahon and Hays, 2006), which regulate their body temperature by adjusting metabolic heat production and insulation from the environment, a trait beneficial especially in the cold. Various degrees of body core insulation in mammals and birds constrain their distribution to either warmer or colder waters (by poor or high insulation, respectively). However, large body sizes enable some aquatic air breathers to travel across the widest temperature ranges possible in some of the largest migrations on Earth.

Changes in water chemistry and hypoxia have minimal direct influences on the air-breathing vertebrates, reflecting their large independence from physical and chemical drivers in the oceans. There is evidence for increased sound propagation in a CO_2-enriched ocean, but no evidence yet for any effect on biota (Ilyina et al., 2010). If habitat structures offering retreat or ambush disappear, this will increase the energetic costs of life. Warming waters increase the cost of pursuit-diving as prey fishes increase swimming velocity. The predation success of such mammals (e.g., sea lions) and seabirds (e.g., penguins, cormorants) is thus constrained to waters ≤20°C (Cairns et al., 2008), a trend that extrapolates into the future (*low* to *medium confidence*). As prey distributions shift, foragers tied to land between trips may be constrained by the physiological costs of finding prey (Péron et al., 2012; Hazen et al., 2013). If food items are only found in thermally restricted areas or move to greater depths, mammals and birds may become constrained to certain distribution ranges or to the physiological limits of their diving ability (McIntyre et al., 2011). Conversely, hypoxic habitat compression for fishes may facilitate foraging opportunities for their air-breathing predators (Hazen et al., 2009). Accordingly, many air-breathers encounter changing habitat and food availability with climate change (*high confidence*).

6.3.7.2. Field Observations

Some species of seabirds, marine mammals, and sea turtles have responded to the anomalous ocean climate of the 20th century (*high confidence*; Hughes, 2000). There is insufficient information to assess effects on sea snakes or crocodiles. Poleward distribution shifts of turtles consistent with recent warming have been recorded in almost all marine groups. Decadal-scale climate fluctuations affect their recruitment success and nesting abundance (Van Houtan and Halley, 2011), with an inverse correlation between warming and abundance in various species and regions (Balazs and Chaloupka, 2004; Chaloupka et al., 2008; Mazaris et al., 2009). Extreme weather causes nest flooding, considerably reducing hatching success (Van Houtan and Bass, 2007); projected sea level rise (WGI AR5 Chapter 13) will exacerbate such impact. Those with high fidelity to nesting and foraging sites (Cuevas et al., 2008) are impacted more than those capable of changing those sites (Fish et al., 2009; Hawkes et al., 2009). Continued warming, modulated by changing rainfall (Santidrián Tomillo et al., 2012), may skew turtle sex ratios toward females, increase egg and hatchling mortality (Fuentes et al., 2009), cause earlier onset of nesting (Pike et al., 2006; Mazaris et al., 2008), decrease nesting populations (Chaloupka et al., 2008), and shift dietary breadths (Hawkes et al., 2009), leading to projected recruitment declines (e.g., leatherback turtles; Saba et al., 2012). Vulnerability due to shifting sex ratio alone remains unclear, as nesting beaches have persisted with low production of male hatchlings over decades or longer (*low confidence*; Godfrey et al., 1999; Broderick et al., 2000; Hays et al., 2003). The absence of sea turtles in certain regions may be best explained by the temporal unavailability of food resources or strong thermoclines restricting their bottom foraging abilities (Braun-McNeill et al., 2008; Gardner et al., 2008).

Seabird range modifications probably caused by climate change were recorded in polar areas and the temperate zone of the North Atlantic (Grémillet and Boulinier, 2009). Temperate species have shifted their ranges to higher latitudes in both hemispheres (Bunce et al., 2002; Robinson et al., 2005; La Sorte and Jetz, 2010). Some species, like the king penguin, follow shifting foraging zones (Péron et al., 2012); others, such as the emperor penguin, are affected by changing habitat structure (sea ice; Jenouvrier et al., 2012). Warming causes many bird species to breed earlier (Sydeman and Bograd, 2009). High-latitude, cool-water species undergo extended breeding seasons (Chambers et al., 2011). There is often no agreement, whether changes reflect solely ocean warming, or a combination of factors, such as fishing pressure on seabirds' prey species, sea level rise, and pollution (Galbraith et al., 2005; Votier et al., 2005; Heath et al., 2009). Most shifts in range and seasonal activity involve shifts in trophic relationships (*medium confidence*). Seabirds with narrow geographic domains are expected to be more susceptible to climate change (Chambers et al., 2005; Grémillet and Boulinier, 2009), even leading to local extinctions (e.g., the Galápagos penguin: Vargas et al., 2007; or the marbled murrelet: Becker et al., 2007).

The distribution, phenology, and migratory timing of marine mammals are also shaped by predator-prey dynamics and climate impacts on specific habitats (Calambokidis et al., 2009; Salvadeo et al., 2011). Some marine mammals, that is, dolphin, porpoise, and whale species, shift their distribution poleward to follow the movement of their prey (*medium confidence*; Springer et al., 1999; MacLeod et al., 2005; Simmonds and Isaac, 2007; Salvadeo et al., 2010). As in birds, vulnerability to climate change is high for marine mammals with narrow geographic ranges and high habitat dependence. For example, the critically endangered vaquita, endemic to the Northern Gulf of California, cannot move north because of the land barrier (MacLeod, 2009). The polar bear (Laidre et al., 2008; Rode et al., 2012) and the walrus depend on sea ice as a platform for hunting, resting, and giving birth. For polar bears, access to prey such as ringed seals has been disrupted by the later formation and earlier breakup of sea ice in the eastern Canadian Arctic. Seasonal migrants into the Arctic (fin, minke, gray, killer, humpback whales) may increasingly compete with species adapted to operate in habitat with sea ice (some seals, narwhal, bowhead whale, beluga). Both may benefit from the net loss of sea ice, which will offer them better access to foraging in a pelagic-dominated ecosystem (Moore and Huntington, 2008).

6.3.8. Summary and Conclusions

An organism's capacity to perform, but also its access to food energy fueling that performance, shape its sensitivity to climate change (*high confidence*). Extreme temperatures surpassing the fringes of the thermal envelope cause local abundance losses, extinction, and shifts in temperature-dependent distribution ranges (*high confidence*; Section 6.3.1).

Some climate change effects detected in the field can be attributed to temperature, but few allow clear attribution to other drivers (Sections 6.3.1-5, 6.6). In fishes and invertebrates, specialization in regional climate regimes co-defines sensitivity to warming, acidification, and hypoxia (*high confidence*; Section 6.3.5). In marine mammals, birds, and ectothermic reptiles, changes in life history and population dynamics have often not been directly attributed to climate drivers (*low confidence*), but rather to the availability of habitat and food (*high confidence*; Section 6.3.7).

Natural climatic variability (Figure 6-1) and anthropogenic change, with a strong role of warming, cause large-scale changes in biogeography, abundance, diversity, community composition, and structure of marine species (*very high confidence*; Section 6.3.1). Warming reduces body size (*medium confidence*; Section 6.3.1). Differential species responses modify their interactions across trophic levels through trophic amplification (*medium* to *high confidence*; Section 6.3.6).

Some tropical species and ecosystems exist close to upper thermal limits placing them among the marine ecosystems most affected by climate change (*high confidence*; Section 6.3.1). Corals and coral reefs are primary examples. However, other factors change concomitantly, such that quantifying ecosystem changes attributable to warming or other drivers has not always been possible (Section 6.3.5).

Under future climate change ocean acidification will affect marine organisms and ecosystems for centuries (*high confidence*; Sections 6.3.2, 6.3.5). To date, very few ecosystem-level changes in the field have been attributed to anthropogenic or local ocean acidification (*medium confidence*; Section 6.3.2). Concomitant trends of warming, O_2 depletion, OA, and other drivers prevent clear attribution to OA (Section 6.3.5).

Elevated CO_2 levels stimulate primary production of some macroalgae and seagrass species (*high confidence*), causing them to be more competitive than calcifying organisms (*medium confidence*; Section 6.3.2). High sensitivities to OA are associated with low capacities to maintain pH in internal fluids (*high confidence*). Calcification rates in sensitive invertebrates, including corals, echinoderms, and mollusks, decrease under OA, especially if combined with temperature extremes

Frequently Asked Questions

FAQ 6.4 | What changes in marine ecosystems are likely because of climate change?

There is general consensus among scientists that climate change significantly affects marine ecosystems and may have profound impacts on future ocean biodiversity. Recent changes in the distribution of species as well as species richness within some marine communities and the structure of those communities have been attributed to ocean warming. Projected changes in physical and biogeochemical drivers such as temperature, CO_2 content and acidification, oxygen levels, the availability of nutrients, and the amount of ocean covered by ice will affect marine life.

Overall, climate change will lead to large-scale shifts in the patterns of marine productivity, biodiversity, community composition, and ecosystem structure. Regional extinction of species that are sensitive to climate change will lead to a decrease in species richness. In particular, the impacts of climate change on vulnerable organisms such as warm-water corals are expected to affect associated ecosystems, such as coral reef communities.

Ocean primary production of the phytoplankton at the base of the marine food chain is expected to change but the global patterns of these changes are difficult to project. Existing projections suggest an increase in primary production at high latitudes such as the Arctic and Southern Oceans (because the amount of sunlight available for photosynthesis of phytoplankton goes up as the amount of water covered by ice decreases). Decreases are projected for ocean primary production in the tropics and at mid-latitudes because of reduced nutrient supply. Alteration of the biology, distribution, and seasonal activity of marine organisms will disturb food web interactions such as the grazing of copepods (tiny crustaceans) on planktonic algae, another important foundational level of the marine food chain. Increasing temperature, nutrient fluctuations, and human-induced eutrophication may support the development of harmful algal blooms in coastal areas. Similar effects are expected in upwelling areas where wind and currents bring colder and nutrient-rich water to the surface. Climate change may also cause shifts in the distribution and abundance of pathogens such as those that cause cholera.

Most climate change scenarios foresee a shift or expansion of the ranges of many species of plankton, fish, and invertebrates toward higher latitudes, by tens of kilometers per decade, contributing to changes in species richness and altered community composition. Organisms less likely to shift to higher latitudes because they are more tolerant of the direct effects of climate change or less mobile may also be affected because climate change will alter the existing food webs on which they depend.

In polar areas, populations of species of invertebrates and fish adapted to colder waters may decline as they have no place to go. Some of those species may face local extinction. Some species in semi-enclosed seas such as the Wadden Sea and the Mediterranean Sea also face higher risk of local extinction because land boundaries around those bodies of water will make it difficult for those species to move laterally to escape waters that may be too warm.

(*high confidence*; Section 6.3.5). Thresholds beyond which effects occur can be quantified only with *low confidence*; there are differential sensitivities and thresholds between taxa and species (*high confidence*; Section 6.3.2).

Expansion of oxygen minimum zones leads to community shifts clearly attributable to extreme hypoxia (*high confidence*; Section 6.3.3). Gradual effects of a progressive decline in ocean O_2 levels on communities have not been sufficiently explored.

In general, community reassembly with new species coming in will occur in the transition to future climates (*medium confidence*) and lead to new ecosystem states (*low confidence*; Section 6.3.6). Climate change interacts with top-down human interferences, such as fisheries or other forms of harvesting, which accelerate impacts (*medium confidence*). Nonlinearities challenge the projection of marine ecosystem trajectories (FAQ 6.4).

In microbes, a conceptual foundation suitable to support an integrated understanding of climate impacts on individual species and communities is lacking. Specific physiological responses, such as in primary production, N_2 fixation, or calcification, can be attributed to multiple environmental drivers associated with climate change (*high confidence*; Sections 6.3.1-5).

6.4. Human Activities in Marine Ecosystems: Adaptation Benefits and Threats

Human societies benefit from resources and processes supplied by marine ecosystems, so-called ecosystem services. Attributing and projecting ecosystem changes and their effects on human communities caused by climate change including ocean acidification is challenging. Insufficient observations compound an understanding of long-term changes and the definition of baseline conditions. Some of the challenges are related to the difficulty of projecting how human communities will adapt to changing marine ecosystem benefits.

6.4.1. Ecosystem Services

Marine ecosystem services (e.g., Chapter 5) include products (food, fuel, biochemical resources), climate regulation and biogeochemical processes (CO_2 uptake, carbon storage, microbial water purification), coastal protection, provision of space and waterways for maritime transport, cultural services (recreational and spiritual opportunities, aesthetic enjoyment), and functions supporting all other ecosystem services (nutrient cycling, photosynthesis, habitat creation). Most components of the marine environment contribute to more than one major category of ecosystem service: for example, ocean primary productivity is classified as a supporting service, but it affects provisioning services via changes in fisheries, generation of fossil fuel resources, regulating services via the global carbon cycle and climate regulation, and cultural services via the enjoyment of a healthy ecosystem. Rarely has economic damage of climate change to a whole ecosystem been evaluated and projected. The projected loss of tropical reef cover due to ocean acidification under SRES A1 and B2 scenarios will cause damages of US$870 and 528 billion (year 2000 value) by 2100, respectively (cost rising with parallel economic growth; Brander et al., 2012; see also Box CC-OA). Such loss is felt most strongly in the respective regions.

6.4.1.1. Food from the Sea

Fisheries provide 3 billion people with almost 20% of their average per capita intake of animal protein (FAO, 2012a), 400 million depend critically on fish for their food (Garcia and Rosenberg, 2010). Total world marine capture fisheries catches stabilized in the mid-1990s at about 90 million tons per year. Marine aquaculture of primarily mollusks and crustaceans contributes more than 63 million tons annually to seafood production, mostly concentrated in coastal areas (FAO, 2012b). The growth of aquaculture has decelerated, but is still considered a development opportunity and a strong need in regions such as Africa and Latin America (Section 7.4.2.2).

Climate-induced shifts in ecosystems and fisheries production will create significant challenges to sustainability and management (Section 7.5.1.1.3), particularly for countries with fewer resources and lower adaptive capacity, including many low-latitude and small island nations (*high confidence*; Allison et al., 2009; Worm et al., 2009; Cooley et al., 2012; see also Sections 7.2.1.2, 7.4.2.1, 30.6.2; WGIII AR5 Section 2.1). Vulnerability will be exacerbated by increases in the frequency and severity of extreme events (e.g., floods or storms) damaging infrastructure, homes, health, livelihoods, or non-marine food security (Kovats et al., 2003; Rosegrant and Cline, 2003; Adger et al., 2005; Haines et al., 2006).

The projected trends in fish stocks will widen the disparity in food security between developing and developed nations. Fish migrations due to warming (Section 6.3.1) have already shifted the composition of fisheries catches (Pinsky and Fogarty, 2012; Cheung et al., 2013a) and altered stock distributions (Sabatés et al., 2006). Further warming may be beneficial for fisheries productivity in some regions such as the North Atlantic, because of the poleward shift of exploited species and changes in primary productivity (Arnason, 2007; Stenevik and Sundby, 2007; Cheung et al., 2010; see also Box 6-1; Section 30.5.1.1.1), or for some Pacific Islands due to the eastward redistribution of tuna stocks (Lehodey, 2000; Lehodey et al., 2011). Resulting changes in accessibility and fishing operations costs are projected to straddle economic zones, perturb international fishery agreements, and cause excessive exploitation (Hannesson, 2007; Sumaila et al., 2011; see also Sections 7.3.2.4, 7.4.2; WGIII AR5 Section 4.3.7).

Invertebrate fisheries and aquaculture appear very vulnerable to the impacts of ocean acidification (Barton et al., 2012; see also Box CC-OA; Figure 6-10). This concerns especially shelled mollusks, with a substantial decline in their global production projected between 2020 and 2060 under the SRES A2 business-as-usual scenario (Cooley and Doney, 2009; Cooley et al., 2012). Effects on calcifying plankton will propagate through the food web, making estimates of economic impact on fish catch by OA difficult, also due to complex interactions with other stressors like warming and fisheries management (Griffith et al., 2012; Branch et al., 2013). Model projections suggest a potential loss of up to 13% (SRES A1FI scenario) to annual total fishery value in the USA, or globally more than US$100 billion annually by 2100 (Cooley and Doney, 2009; Narita et al., 2012). Vulnerability differs highly between nations according to the contribution of such fisheries to their economy (Cooley et al., 2012; see also Sections 7.3.2.4, 7.4.2). These projections are sensitive to the projected vulnerabilities of the organisms to ocean acidification (*medium confidence*; Section 6.3.2).

Fishing reduces abundances at high trophic levels, but increases abundances at mid-trophic levels. It reduces species numbers, simplifies ecosystem structure, and increases ecosystem sensitivity to climate change (Perry et al., 2010). Exploitation of fish stocks and the alteration of their demography, population dynamics, and life history traits (Petitgas et al., 2006; Perry et al., 2010; Planque et al., 2010) can reduce the capacity of fish populations to buffer changes in climate variability (Ottersen et al., 2006; Genner et al., 2010), and increase variability in population size. Interactions between warming, OA, and human activities such as fishing may thus exacerbate climate impacts on a wide range of ocean processes and services, including marine fisheries (*medium confidence*; Tables 6-4, 6-6; Section 30.6.2).

A 2°C global temperature increase by 2050 is estimated to cause global losses in landed value of US$17 to 41 billion annually (in 2005 value), with an estimated cost of adaptation for the fisheries of US$7 to 30 billion annually over a 40-year time frame between 2010 and 2050. The largest loss in landed value is projected to occur in East Asia and the Pacific (*low confidence*; Sumaila and Cheung, 2010). Overall impacts and the regional manifestations will partially depend on the flexibility and response capacities of food production systems (Elmqvist et al., 2003; Planque et al., 2011a).

Specific implications for the fishing industry are still poorly known, as future projections of shifts in primary production and knock-on effects through food webs and into fisheries remain uncertain (*low confidence* in effects of changing NPP; Planque et al., 2011b; Stock et al., 2011).

6.4.1.2. Other Provisioning Services

Reductions in marine biodiversity due to climate change and other anthropogenic stressors (Tittensor et al., 2010), such as OA (CBD, 2009) and pollution, might reduce the discovery of genetic resources from marine species useful in pharmaceutical, aquaculture, agriculture, and other industries (Arrieta et al., 2010), leading to a loss of option value from marine ecosystems. Climate change increases the demand for marine renewable energy such as wind and wave power, though with potential ecosystem impacts of their infrastructure (Section 6.4.2).

6.4.1.3. Climate Regulation and Extreme Events

The effect of climate change on marine biota will alter their contribution to climate regulation, that is, the maintenance of the chemical composition and physical processes in the atmosphere and oceans (*high confidence*; Beaumont et al., 2007). Regulatory mechanisms in which organisms (especially phytoplankton) play a key role, include control of the level of atmospheric CO_2 through the balance between photosynthesis and respiration (Johnson et al., 2010), and through the biological and alkalinity pump (Falkowski, 1997; Feely et al., 2008). They also include the modulation of further greenhouse gases such as nitrous oxide (N_2O; Jin and Gruber, 2003; Law, 2008; see also Section 6.1.1.3), and the modulation of other climatically reactive gases such as dimethylsulfide (DMS; Vogt et al., 2008). A projected decrease in global ocean NPP (Section 6.5.1) may result in decreased export of biogenic carbon to the deep ocean (Bopp et al., 2002; Boyd and Doney, 2002; Hashioka and Yamanaka, 2007). A positive feedback on climate change may result; however, many of the factors controlling the pump are poorly understood (Figure 6-4; WGI AR5 Chapter 6).

Coastal marine ecosystems reduce the effects of floods and storm surges which account for most of the natural disasters affecting people in coastal regions (IPCC, 2012a). Empirical and modeling studies show that coral reefs contribute to buffering the impact of tsunamis (Fernando et al., 2005; Gravelle and Mimura, 2008; see also Sections 5.4.2.4, 30.5; Box CC-CR). Experiments and models indicate that warming and OA slow coral growth by nearly 50% by 2050 (Box CC-CR; Section 5.4.2.4), making some islands and coastal areas more vulnerable to tsunamis, storm surges, wave energy, and coastal erosion (*high confidence*). Wetlands and mangroves provide biologically diverse buffer zones (Section 5.4.2.3). The combined impacts of climate change, pollution, deoxygenation, and other overlapping stressors, on mangroves and wetlands have not been determined (Cooley et al., 2009; Cooley, 2012). Some of these stressors enhance each other's effects in coastal systems (Feely et al., 2010; Cai et al., 2011; Howarth et al., 2011).

6.4.1.4. Cultural Services

Cultural services encompass a wide array of services with marine biodiversity as a core component supporting recreation and tourism as the economically most relevant. Tropical coral reefs and their enormous biodiversity sustain substantial tourist industries, presently with global annual net benefits of about US$9.6 billion (Cesar et al., 2003; see also Box CC-CR; Section 30.6.2.2). If reef services degrade, coastal visitors might choose alternative attractions (UNWTO, 2008). Increased travel to see disappearing ecosystem types (e.g., Antarctica: Liggett et al., 2011) or in previously inhospitable areas or seasons (Amelung et al., 2007; Moore, 2010) create new pressures and are unsustainable as the locations of key attractors shift (e.g., cetaceans: Lambert et al., 2010; Salvadeo et al., 2013).

Climate change may endanger harvests of marine species with spiritual and aesthetic importance to indigenous cultures, raising ethical questions about cultural preservation (e.g., Nuttall, 1998). In coastal communities, losing the aesthetic values of marine ecosystems may harm local economies: better water quality and fewer harmful algal blooms are related to higher shellfish landings and real estate prices (Jin et al., 2008).

Some heritage benefits of preserving marine ecosystems consist of the economic value of a healthy, diverse ecosystem to future generations. Any climate-related biodiversity loss or pollution of marine ecosystems would decrease the bank of resources for future opportunities. For example, the research and conservation value of coral reef biodiversity and its non-use value are estimated together at US$5.5 billion annually (Cesar et al., 2003). As with spiritual and aesthetic benefits, maintaining heritage benefits under climate change poses challenges for managers concerning equity and ethics as well as multigenerational (and possibly multi-cultural) ethical questions.

6.4.1.5. Supporting Services

Fully identifying the services supporting other ecosystem benefits is virtually impossible, as they are diverse in nature and scale. Ecosystem engineers play an important role in these services. Damage to calcifying algae and corals will reduce habitat for other species (Section 6.3.5), biodiversity, cultural and leisure values, and their climate regulation capacity.

Waterways for shipping are expected to change in the next several decades (*very high confidence*; Chapter 28; Section 30.6.2.3). Reductions in Arctic sea ice allow new trade routes such as the Northwest Passage (Wilson et al., 2004; Granier et al., 2006), enabling economically viable trans-Arctic shipping, and access to regional resources for exploitation and tourism. This development would increase emission of greenhouse gases and other pollutants (Lauer et al., 2009; Corbett et al., 2010), and facilitate the invasion of non-indigenous species carried on hulls and in ballast waters (Lewis et al., 2004).

6.4.2. Management-Related Adaptations and Risks

6.4.2.1. Ecosystem Management

A changing climate will have both positive and negative consequences for managing ocean resources (*high confidence*) (Eide and Heen, 2002;

Eide, 2007; see also Section 6.4.1). Ecosystem-based management (EBM, an approach recognizing all, including human interactions, within an ecosystem) or the ecosystem approach (EA, a strategy for the integrated management of living resources promoting both conservation and sustainable use) are increasingly adopted globally (FAO, 2003) to deal with the multitude of human pressures on marine ecosystems (Sherman et al., 2005; Hoel, 2009). Extended EBM addresses changes driven by climate and human activities, considering that diverse drivers will interact and confound each other (Planque et al., 2010; Eero et al., 2011; see also Section 6.3.5). Human activities will undermine resilience to other, including climate, impacts or undermine the effectiveness of mitigation and adaptation measures, by increasing variability (thereby reducing predictability), and limiting scope for adaptation (*high confidence*; e.g., Hughes, 2004; Sissener and Bjørndal, 2005; Eero et al., 2011). Thus, managing ecosystems under climate change increases the resilience of ecosystems and adaptive capacity of management systems through reducing other human perturbations (e.g., overfishing) (Brander, 2008; see also Section 7.5.1.1.3). Managing ecosystems also reduces the consequences of ocean acidification until CO_2 emission reduction becomes effective (Rau et al., 2012; Billé et al., 2013; McLeod et al., 2013; see also Box CC-OA). Ecosystem resilience is enhanced by reducing regional eutrophication (Falkenberg et al., 2013), or in aquaculture by avoiding acidified water (Barton et al., 2012) and by selecting and cultivating pre-adapted strains (Parker et al., 2012).

However, effects of climate change cannot be reversed by reducing the impacts of non-climatic drivers, emphasizing the need for adaptive management. Increased variability of ecosystem responses to climate change and the low predictability of some biological responses undermine the effectiveness of management and conservation measures. A particular risk is that climate change may contribute to large-scale ecosystem regime shifts (Section 6.3.1.5; Box 6-1). Detecting and forecasting such shifts from time series of environmental and biological data (Carpenter and Brock, 2006; deYoung et al., 2008), is constrained by an insufficient number of observations and limited quantitative understanding (Section 6.1.2). Biogeographic shifts challenge spatial management (Box CC-MB; Sections 6.3.1, 6.5), which is a fundamental part of EBM (Douvere, 2008), and demand that "fixed in law forever" site-attached zoning to protect specific species may need to become more flexible to maintain the original objectives as species move or community structures shift (*high confidence*; Soto, 2001; Hawkins, 2012).

6.4.2.2. Geoengineering Approaches

Geoengineering approaches to mitigate climate change and its effects, include Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR; see Table 6-5; IPCC, 2012b). SRM aims to reduce warming by increasing albedo, for example, via stratospheric injection of sulfate aerosol (Crutzen, 2006). SRM may affect marine ecosystems through changes in precipitation. With continued CO_2 emissions it leaves ocean acidification largely unabated as it cannot mitigate rising atmospheric CO_2 concentrations (Vaughan and Lenton, 2011; Williamson and Turley, 2012). Termination of SRM after its implementation involves the risk of rapid climate change and more severe effects on ecosystems (Russell et al., 2012).

Proposed CDR techniques include both ocean- and land-based approaches (Vaughan and Lenton, 2011; see also Section 30.6.4). CO_2 storage in geological reservoirs may occur beneath the seafloor, for example, in porous marine aquifers, and includes the risk of CO_2 leakage to the marine environment. Proposals to directly or indirectly sequester CO_2 into the ocean (Caldeira et al., 2005; Boyd, 2008; Shepherd et al., 2009; see also Table 6-5; WGIII AR5 Section 7.5.5) include, among others, the use of ocean fertilization techniques by nutrient addition, the direct storage of biomass in the deep ocean, the addition of alkalinity for build-up of dissolved inorganic carbon (DIC; i.e., carbonate), and the direct CO_2 injection into the deep ocean (Williamson et al., 2012). All of these approaches have potentially negative consequences for marine ecosystems.

Ocean fertilization by adding iron to high-nutrient low-chlorophyll (HNLC) oceanic waters could increase productivity and the net export of organic material to the deep ocean and its consecutive decomposition, causing deep-water accumulation of CO_2. Fertilization would affect all major marine biogeochemical cycles of the ocean with unclear side effects that could include the formation of methane (CH_4) and N_2O (Law, 2008) or the stimulation of harmful algal blooms (Trick et al., 2010). The enhanced NPP would add more carbon to the base of food webs (de Baar et al., 2005) and stimulate growth, for example, of deep-sea benthos (Wolff et al., 2011). Any regional increase in organic material (through fertilization or intentional storage of biomass) would cause enhanced O_2 demand and deep-water O_2 depletion (Sarmiento et al., 2010; Table 6-5), increasing the level and extent of hypoxia and associated impacts on marine ecosystems (Sections 6.3.3, 6.3.5, 30.5.7). The synergistic effects of CO_2-induced acidification will exacerbate the biological impacts (*high confidence*).

Neutralizing the acidifying water by the addition of alkalinity, for example, calcium oxide, would require large-scale terrestrial mining with associated consequences (Caldeira et al., 2005). The biological effects of increased concentrations of Ca^{2+} ions and dissolved inorganic carbon remain insufficiently explored. Direct injection of CO_2 or its localized disposal in the ocean (e.g., as a lake in a deep-sea valley) causes locally highly increased CO_2 and acidification effects on deep-sea organisms (*high confidence*; Caldeira et al., 2005; see also Section 6.3.3.4). In contrast to long-term ocean fertilization or storage of biomass, this technique leaves the oxygen inventory of the deep ocean untouched (*limited evidence*, *medium agreement*; Pörtner et al., 2005).

The knowledge base on the implementation of SRM and CDR techniques and associated risks is presently insufficient. Comparative assessments suggest that the main ocean-related geoengineering approaches are very costly and have large environmental footprints (*high confidence*; Boyd, 2008; Vaughan and Lenton, 2011; Russell et al., 2012).

6.4.2.3. Health Issues

Human health and near-shore ecosystems may be directly impacted by climate change effects on harmful algal blooms (HABs; Edwards et al., 2006; see also Section 30.6.3) or disease vectors. Planktonic time-series archives and nearshore sediment cores containing HAB cysts have revealed few examples of strong linkages between altered HABs and

Table 6-5 | Challenges for the oceans that will arise from the employment of a range of geoengineering methods (SRM = solar radiation management; CDR = carbon dioxide removal).

Topic	Brief description	Challenge and impact	References
Solar radiation management techniques	Deflection of approximately 1.8% of sunlight, by various techniques, is able to offset the global mean temperature effects of a doubling of atmospheric CO_2 content from pre-industrial values.	Will leave ocean acidification unabated (*high confidence*). Response of primary production to light reduction unclear.	Crutzen (2006); Caldeira and Wood (2008)
Ocean storage by direct injection	Capture of CO_2 post-combustion from mainly coastal power plants, followed by injection of liquid CO_2 by pipeline or from a ship into the deep ocean.	Will add to ocean acidification and create localized harm to marine life (*high confidence*). Quantities will be small relative to the atmospheric invasion signal. CO_2 injected will dissolve and be transported by ocean circulation with eventual surface exposure.	Caldeira et al. (2005)
Sub-sea geologic storage	Capture of CO_2 from extracted gas or from post-combustion followed by well injection into a porous submarine aquifer beneath impermeable geologic strata.	Extensive experience in place from the Norwegian Sleipner field activity in the North Sea. No evidence of ocean impact from leakage to date.	Benson et al. (2005)
Ocean fertilization	Spreading of trace amounts of reduced iron over very large areas of the surface ocean where excess nutrients occur. Overcoming the local iron deficiency creates extensive phytoplankton blooms drawing down sea surface pCO_2. Fertilization can also be carried out by using direct or indirect (ocean pipes) addition of macronutrients to oceanic regions where they are depleted.	Much of the exported organic matter is remineralized at shallow depths, creating local oxygen stress and shallow CO_2 enrichment and methane and N_2O production. These effects are temporary and the effective retention time is short. If sustained, reduced surface ocean and increased deep ocean acidification. O_2 loss in ocean interior (*medium confidence*).	de Baar et al. (1995); de Baar et al. (2005); Pörtner et al. (2005); Boyd et al. (2007); Buesseler et al. (2008); Law (2008); Cao and Caldeira (2010)
Artificial upwelling or downwelling	Ocean fertilization by bringing nutrient rich deep water (from 200 to 1000 m) to the surface. Downwelling occurs in parallel, transporting physically dissolved CO_2 into the deep ocean.	Deep water contains high levels of CO_2, which if released counteracts the binding of CO_2 by fertilization. No evidence available.	Lovelock and Rapley (2007); Oschlies et al. (2010)
Sequestration of organic carbon	Storage of terrestrial biomass in the coastal or deep ocean.	Physical impact, regional loss of oxygen, CO_2 accumulation and acidification during degradation; increases in methane, N_2O, and H_2S. No evidence available.	Metzger and Benford (2001); Strand and Benford (2009)
Carbonate neutralization	Dissolution of power plant flue gas into sea water yielding an acidic solution that is neutralized by addition of crushed limestone. The resulting bicarbonate-rich fluid is discharged to the ocean.	Involves the transport and crushing to fine scale of large quantities of limestone and the processing of very large quantities of sea water. Environmental impact issues not yet explored.	Rau (2011)
Accelerated olivine weathering	Uses wind powered electrochemical processes to remove HCl from the ocean and neutralizes the acid with silicate minerals such as olivine for disposal. The net result is to add alkalinity to the ocean akin to natural silicate weathering processes.	Complex system as yet untested in pilot processes. Involves mining and crushing large quantities of silicate minerals. Very long time scale consequences uncertain.	House et al. (2007); Köhler et al. (2010)

climate fluctuations (Dale et al., 2006; see also Section 30.5.3.1.2). HABs can be stimulated by warming, nutrient fluctuations in upwelling areas, eutrophication in coastal areas, and enhanced surface stratification (*medium confidence*). Species-specific responses involve shifts in seasonal cycles and blooms (Johns et al., 2003). Ocean acidification may exacerbate the toxicity of species in coastal oceans under nutrient-limited conditions (Tatters et al., 2012; Sun et al., 2011). Suitable adaptation measures include appropriate monitoring of biotoxin problems (Hallegraeff, 2010).

Continued warming of tropical and temperate coastal habitats, excessive nutrient loading leading to phytoplankton and zooplankton blooms, and sea water inundation due to sea level rise are all projected to exacerbate the expansion and threat of cholera (*medium confidence*; see also Sections 11.5.2.1, 30.6.3), although attribution to climate change is confounded by climate variability and non-climate drivers (Lafferty, 2009; Dobson, 2009).

Cholera and its pathogen, the marine bacterium, *Vibrio cholera*, have been widely studied. The pathogen associates with marine organisms, especially chitinized zooplankton (Vezzulli et al., 2010). Where cholera is endemic (e.g., India, Bangladesh, Latin America), outbreaks correlate with warming and high zooplankton abundance (Lobitz et al., 2000; Lipp et al., 2002). Based on an 18-year climate record for Bangladesh, Pascual et al. (2000) reported cholera outbreaks at ENSO events, and the recent reappearance of cholera in Peru has also been linked to the intense 1991–1992 ENSO (Lipp et al., 2002). An increase in sustained maximum temperatures of the Baltic Sea (Section 30.5.3.1.4) has been related to an increase in reported *Vibrio* infections; highest human mortality rates were associated with *V. vulnificus* infections (Baker-Austin et al., 2013). Continued warming of tropical and temperate coastal habitats, excessive nutrient loading leading to phytoplankton and zooplankton blooms, and seawater inundation due to sea level rise are all projected to exacerbate the expansion and threat of cholera (*medium confidence*).

Ciguatera poisoning may occur when people consume fish, mainly from tropical reefs, that have ciguatoxins from the epiphytic dinoflagellate *Gambierdiscus* sp. Historical records show significant correlations between ciguatera poisoning and sea surface temperature in South Pacific nations (Hales et al., 1999). However, the relationship is nonlinear and dependent on the thermal window of the specific dinoflagellate (Llewellyn, 2010). This casts doubt on the accuracy of projected increases in ciguatera poisoning using linear extrapolations from observations (*low confidence*).

6.4.3. Conclusions

Human societies benefit from and depend on marine ecosystem services, including the provisioning of food and other goods, regulation of climate and extreme events, and cultural and supporting services (Section 6.4.1). Attributing and projecting climate-change-mediated shifts in these services remains a challenge, due to the intrinsic difficulty of assessments, lack of baseline and long time series data, and confounding human impacts. However, empirical and modeling studies indicate that climate change impacts on marine ecosystems lead to changes in provisioning, regulating, and supporting services (*high confidence*), as well as cultural services (*limited evidence*, *medium agreement*).

Food production from the sea is facing diverse stressors (Section 6.4.1.1), such as overfishing and habitat degradation, which interact with climate change phenomena, including warming (Section 6.3.1), ocean acidification (Section 6.3.2), and hypoxia (Section 6.3.3). Projections of impacts on capture fisheries are constrained by uncertainties in marine primary production (*medium evidence*, *medium agreement*; Section 6.5.1). Negative effects are projected to be most significant in developing nations in tropical regions (*high confidence*). Nations at higher latitudes may even benefit from climate change effects on ocean ecosystems, at least initially (Section 6.5.3).

Climate change effects on biota will alter their climate regulation through mechanisms such as carbonate production, the biological pump, the balance between photosynthesis and respiration, and the modulation of greenhouse gases (*high confidence*; Section 6.4.1.3). However, projections of the direction and magnitudes of feedbacks are at an early stage (*low confidence*).

Future management of ecosystems and fisheries might have to aim for increasing ecosystem resilience to climate change, for example, through reductions of other human perturbations (Section 6.4.2.1). Active ocean geoengineering strategies to ameliorate climate change may prove detrimental to the functioning of ecosystems, which highlights the need for further research and careful governance (Section 6.4.2.2). There is limited understanding of how harmful algal blooms and pathogens affecting human health will respond to climate change (Section 6.4.2.3; *medium* to *low confidence*).

6.5. Projections of Future Climate Change Impacts through Modeling Approaches

A range of models explore climate change effects on marine biota, from primary producers to higher trophic levels, and test hypotheses about responses of marine species, food webs, and ecosystems (Rose et al., 2010; Fulton et al., 2011; Stock et al., 2011; see also FAQ 6.2). Both empirical and mechanistic approaches are used over a range of temporal and spatial scales (Barange et al., 2010; Stock et al., 2011). There is an increasing need for upscaling from molecular and physiological to ecosystem level (e.g., Le Quesne and Pinnegar, 2012). Uncertainty in projections of changes in marine ecosystems is partly contingent on the level of confidence in climatic and oceanographic projections (Section 6.1.1; WGI AR5 Section 9.8). Models are currently useful for developing scenarios of directional changes in net primary productivity, species distributions, community structure, and trophic dynamics of marine ecosystems, as well as their implications for ecosystem goods and services under climate change. However, specific quantitative projections by these models remain imprecise (*low confidence*; Hannah et al., 2010; Rose et al., 2010; Stock et al., 2011; FAQ 6.4).

Earth System Models couple atmosphere, cryosphere, and hydrosphere (including the oceans), as well as climate and carbon cycles, and project changes in ocean biogeochemistry under a range of CO_2 emission scenarios (WGI AR5 Chapter 6). Models focusing on population and species level responses comprise models of population dynamics, models of species distribution, and models which explicitly link effects of changes in ocean physics and chemistry to changes in interactions between species at different trophic levels, or human activities such as fishing and aquaculture (Rose et al., 2010).

6.5.1. Oceanic Primary Production

Climate-induced effects on global ocean NPP comprise changes in its long-term average, seasonal timing, and peak amplitude (Henson et al., 2013). The magnitude, direction, and pattern of projected changes vary with differences in model structure and parameterization (Box CC-PP; Figure 6-13). Unknown accuracy of current NPP observations further increases the uncertainty of projections, as does the incomplete understanding of effects of multiple drivers on NPP (Sections 6.3.1-5, 6.4). Global coupled climate-ocean biogeochemical Earth System Models (WGI AR5 Chapter 6) project an increase in NPP at high latitudes but a decrease in permanently stratified oceans at mid-latitudes, in the tropics (west tropical Pacific, tropical Indian Ocean, tropical Atlantic), and in the North Atlantic (*medium confidence*; Steinacher et al., 2010; Bopp et al., 2013) (Figure 6-13). The overall result is a reduction in global mean NPP under all RCP scenarios (*medium confidence* in the direction of projected trends, *low confidence* in the magnitude of change).

6.5.2. Higher Trophic Levels

Projected future changes in temperature and other physical and chemical oceanographic factors are expected to affect the distribution and abundance of marine fishes and invertebrates, as elaborated by species distribution models. Limits of distribution ranges of 1066 exploited species are projected to undergo shifts by a median of around 50 km per decade to higher latitudes by 2050 relative to 2000 under the SRES A1B (≈RCP6.0) scenario (Cheung et al., 2009). Some species shift toward the equator following a regional temperature gradient (Burrows et al., 2011; Cheung et al., 2013b; Pinsky et al., 2013). The rate of range shifts is projected to be three times higher for pelagic than for demersal fishes (Cheung et al., 2009), the latter shifting at a rate of around 27 to 36 km per decade (Cheung et al., 2013b). However, the expansion of hypoxic waters may have a greater impact than warming on demersal fishes (Koslow et al., 2011). As a result of distribution shifts, high-latitude regions (the Arctic, Southern Ocean) are projected to have high rates of species invasions. Intermediate latitudes are expected to undergo both invasions and local extinctions. High rates of local extinction are projected for the tropics and semi-enclosed seas (e.g., Mediterranean Sea, Persian Gulf). In addition, the future productivity and distribution

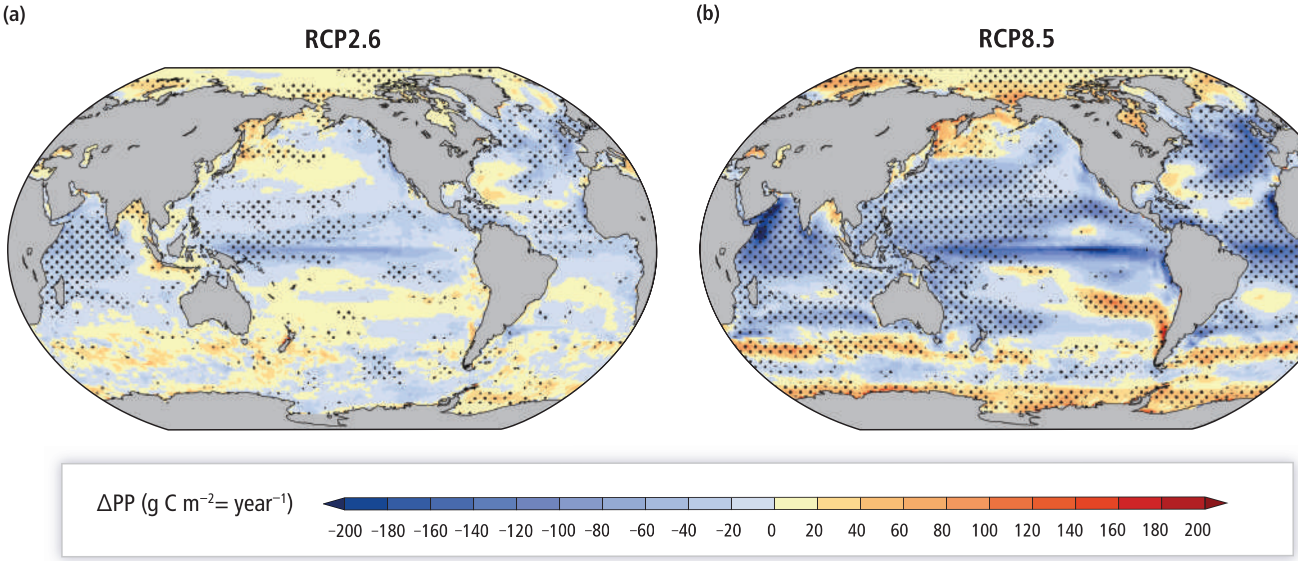


Figure 6-13 | Multi-model annual mean changes of projected vertically integrated net primary production (small and large phytoplankton) under the low-emission scenario Representative Concentration Pathway 2.6 (RCP2.6) (a) and the high-emission scenario RCP8.5 (b) for the period 2090 to 2099 relative to 1990 to 1999 (after Bopp et al., 2013). To indicate consistency in the sign of change, regions are stippled where 80% of the 10 models from the Coupled Model Intercomparison Project Phase 5 (Bopp et al. 2013) agree on the sign of change.

of higher trophic level organisms are projected to change due to changes in primary productivity (Section 6.3.6). For example, the migration route of Pacific sardine is projected to shift because of changes in primary productivity and food availability (Ito et al., 2010). The global pattern of distribution shifts is generally consistent with regional-scale projections and past observations (e.g., Lenoir et al., 2011; Cheung et al., 2013a). However, detailed quantitative projections are sensitive to model structure and assumptions (Hare et al., 2012; Jones et al., 2013) and responses of specific populations may differ from average species responses (Hazen et al., 2013).

Coral reefs are projected to undergo long-term degradation by 2020 to 2100 relative to the 2000s under RCP2.6, 4.5, and 8.5 or their equivalents (Section 30.5.6). Reefs projected to be threatened most by bleaching under the SRES A1B scenario by 2100 include the Central and Western Equatorial Pacific, Coral Triangle, and parts of Micronesia and Melanesia (Teneva et al., 2012). These projections assume that coral bleaching occurs when SST exceeds a certain threshold, and that there is limited potential to shift such threshold by adaptation. Reef degradation will impact ecosystem services (Hoegh-Guldberg, 2011; see also Section 6.4; Box CC-CR).

Some groups of marine air-breathing fauna are projected to shift in distribution and abundance (Section 6.3.7). Cetacean richness will increase above 40° latitude in both hemispheres, while at lower latitudes both pinniped and cetacean richness are projected to decrease by 2040–2049 relative to 1990–1999 under the SRES A1B scenario (Kaschner et al., 2011). Using SST as a predictor, the distribution of loggerhead turtles is projected to expand poleward in the Atlantic Ocean and to gain habitat in the Mediterranean Sea by 2070–2089 relative to 1970–1989 (Witt et al., 2010). Leatherback turtle may decrease in abundance at a rate of 7% per decade because of reduced hatching success with warming following the SRES A2 scenario (Saba et al., 2012). Abundances of some seabirds such as European breeding seabirds (Huntley et al., 2007), Cassin's auklet in the California Current Ecosystem, or emperor penguin in Antarctica are projected to decline because of climate-induced changes in oceanographic conditions, such as temperature and upwelling intensity (Wolf et al., 2010; see also Box CC-UP), or summer sea ice conditions (Jenouvrier et al., 2012). The diversity of megafaunal responses to climate change will have cascading ecosystem impacts, and will affect ecosystem services such as tourism (*high confidence*; Sections 6.3.7, 6.4.1).

6.5.3. Ecosystems and Fisheries

One of the most direct impacts of climate change on marine ecosystem services is through fisheries (Sections 6.4.1, 7.2.1.2, 7.3.2.4, 7.4.2). Projected climate impacts on fisheries are based on recruitment, growth, mortality, abundance, and distribution of fish stocks as well as changes in ocean NPP (Cheung et al., 2008), evaluated from chlorophyll concentration and other variables such as sea surface temperature (Campbell et al., 2002). Friedland et al. (2012) suggested that chlorophyll concentration, indicating both phytoplankton production and biomass, is a better predictor of the fishery yield in large marine ecosystems than NPP. While the principle holds that catch potential is dependent on energy from primary production, quantitative projections of catch potential are limited by residual uncertainty on the best possible indicators of primary production and biomass.

Assuming that the potential fish catch is proportional to NPP, the fish catch in the North Pacific Ocean subtropical biome is projected to increase by 26% through expansion of the biome, while catches in the temperate and equatorial biomes may decrease by 38 and 15%, respectively, through contraction of the biomes by 2100 relative to 2000 under the SRES A2 (RCP6.0 to 8.5) scenario (Polovina et al., 2011). Changes in phytoplankton size structure are projected to affect fisheries catch potential (Cheung et al., 2011), resulting in a 0 up to 75.8% decrease in the potential catch of large fishes in the central North Pacific

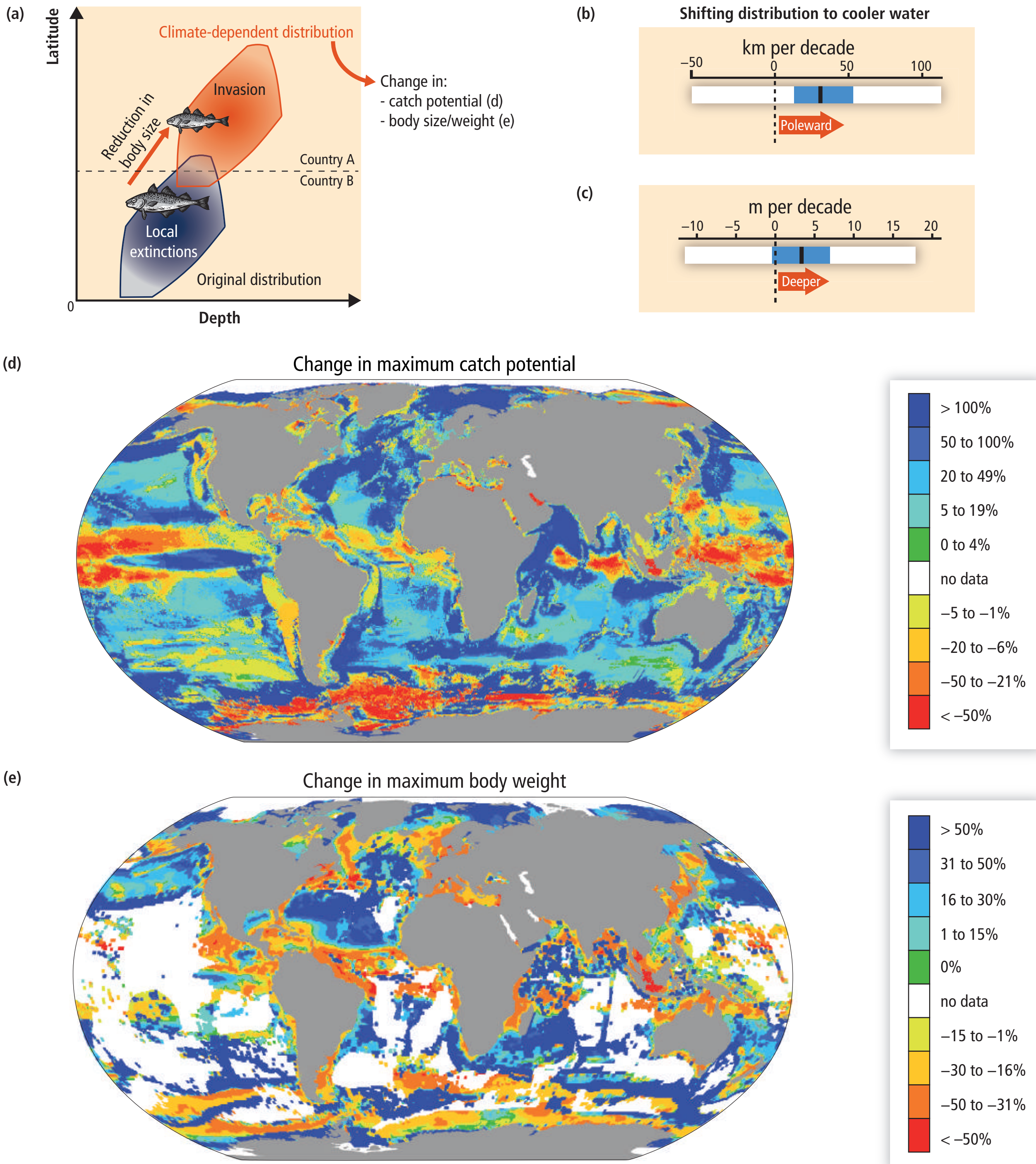


Figure 6-14 | Climate change effects on the biogeography, body size, and fisheries' catch potential of marine fishes and invertebrates. (a) Shifts in distribution range and reduction in body size of exploited fish driven by projected warming, oxygen depletion, and sea ice retreat (cf. Figure 6-7). Whenever the shift in distribution does not fully compensate for warming and hypoxia, the result will be a decrease in body size. Shifts in (b) latitudinal and (c) depth distribution of 610 exploited demersal fishes are projected to have a median (central line of the box) of 31 km per decade and 3.3 m per decade, respectively, with variation between species (box boundary: 25th and 75th percentiles) from 1991–2010 to 2041–2060 under the SRES A2 (between RCP6.0 and 8.5) scenario (Cheung et al., 2011, 2013b). (d) Combining species' range shifts with projected changes in net primary production leads to a projected global redistribution of maximum catch potential. (Analysis includes approximately 1000 species of exploited fishes and invertebrates, under warming by 2°C according to SRES A1B (≈RCP6.0), comparing the 10-year averages 2001–2010 and 2051–2060; redrawn from Cheung et al., 2010.). (e) Changes in species distribution and individual growth are projected to lead to reduced maximum body size of fish communities at a certain site. The analysis includes 610 species of marine fishes, from 1991–2010 to 2041–2060 under SRES A2 (approximately RCP6.0 to 8.5; Cheung et al., 2013b), without analysis of potential impacts of overfishing or ocean acidification. Key assumptions of the projections are that current distribution ranges reflect the preferences and tolerances of species for temperature and other environmental conditions and that these preferences and tolerances do not change over time. Catch potential is determined by species range and net primary production. Growth and maximum body size of fishes are a function of temperature and ambient oxygen level.

and increases of up to 43% in the California Current region over the 21st century under the SRES A2 scenario (Woodworth-Jefcoats et al., 2013). Globally, climate change is projected to cause a large-scale redistribution of global catch potential, with an average 30 to 70% increase in yield at high latitudes and up to 89% in some regions, after 2°C warming from preindustrial periods following SRES A1B (≈RCP6.0) (Cheung et al., 2010; Blanchard et al., 2012; see also Figure 6-14). Redistribution between areas, with average catch potential remaining unchanged, will occur at mid latitudes. A 40 to 60% drop will occur in the tropics and in Antarctica by the 2050s relative to the 2000s (*medium confidence* for direction of trends in fisheries yields, *low confidence* for the magnitude of change). This highlights high vulnerabilities in the economies of tropical coastal countries (Allison et al., 2009; see also Section 6.4).

Fisheries targeting specific species may show more complex responses to climate change. For example, driven by changes in temperature and primary production, catches of skipjack and bigeye tuna in the south Pacific are projected to increase by 2035 relative to 1980–2000 under the SRES B1 and A2 scenario, but for 2100, skipjack tuna catch is projected to decrease under the A2 scenario, while bigyeye tuna catch decreases under both A2 and B1 scenarios (Lehodey et al., 2011). Regionally, tuna catches in the Western Pacific are projected to decrease, while those in the Eastern Pacific will increase (Lehodey et al., 2011). Mollusk fisheries under ocean acidification is discussed under Section 6.4.1.

Identifying responses to climate change is complicated by species interactions and multiple stressors. Major marine habitats and biodiversity hotspots are projected to encounter cumulative impact from changes in temperature, pH, oxygen, and primary productivity by the end of the 21st century (RCP4.5 and 8.5) (Mora et al., 2013). Acidification and hypoxia will reduce maximum catch potential over 50 years from about 2000 onward in both the North Atlantic and Northeast Pacific (Ainsworth et al., 2011; Cheung et al., 2011). Changes in O_2 content as well as warming will drive a global decrease of community-averaged maximum body size of 14 to 24% of exploited demersal marine fishes by 2050 relative to the 2000s under the SRES A2 (RCP6.0 to 8.5) scenario (Cheung et al., 2013b; see also Figure 6-14). The decrease in maximum body size may affect natural mortality rates and trophic interactions, and reduce yield-per-recruit and thus potential catch. Responses of exploited marine species and their fisheries may interact with other human stressors such as overfishing, exacerbating their impacts (e.g., Lindegren et al., 2010; Ainsworth et al., 2011). Through species shifts climate change may also cause overlap of habitats of species targeted by fishing with habitat of threatened species, potentially increasing the chances of the latter of being caught as bycatch (Jones et al., 2013). Moreover, differences in vulnerability and adaptive capacity of species to changing environmental and ecosystem conditions will affect the responses of fisheries to climate change (e.g., Le Borgne et al., 2011; Griffith et al., 2011).

The complex and nonlinear interactions and responses of both biophysical and socioeconomic systems to climate change may lead to changes that have a low probability of occurrence based on empirical data (Doak et al., 2008). The risk of such low-probability but potentially high-impact events may be underestimated in existing model projections (Williams and Jackson, 2007; Lindenmayer et al., 2010). Projected changes in the distribution and production potential of fisheries resources are expected to affect economics, human livelihood, and food security (Allison et al., 2009; Sumaila and Cheung, 2010; *low confidence* in the magnitude and direction of the projected socioeconomic impacts).

6.5.4. Conclusions

Modeling projects that the distribution of invertebrates, fishes, and some marine mammals, birds, and reptiles will shift further under most emission scenarios, with rates and directions of shifts consistent with those observed in the last century (*high confidence*; Sections 6.3.1-7). These projections are valid for those species that adapt not at all or incompletely to warmer temperatures and the associated ecosystem changes, as indicated by present trends (Section 6.3.1; Box CC-MB). For non-adapting species rates of shift will thus increase with increasing rates of warming and higher emission scenarios (*high confidence*), unless the shift is blocked by geographic or other barriers (e.g., light regime; Figure 6-7). The average shift in distribution will continue to be poleward at large spatial scales (*high confidence*; Section 6.5.2; Box CC-MB). Species richness and the abundance of warm-water species will increase at high latitudes (*high confidence*) and decrease in the tropics (*medium confidence*; Section 6.5.2). Projections for individual species and populations are more variable and sensitive to model parameters.

Maximum fisheries catch potential is projected to increase at high and decrease at low latitudes by 2050 under SRES B1 (≈RCP4.5) and A1B (≈RCP6.0) climate scenarios (*medium confidence*; Section 6.5.3). Quantifying such projections is constrained by uncertainties in projected primary production rates (Sections 6.3.4, 6.5.1), biological responses such as species interactions (Section 6.3.6), and in projected effects of multiple climate drivers and human activities (*low confidence*; Section 6.3.5).

Models that integrate climate and ocean changes with biological responses and interactions, and with current human activities, have led to agreement on species and food web responses to climate change (Section 6.5.3). However, most of these models do not include trophic interactions. They insufficiently consider physiological principles and none include evolutionary adaptations that affect responses of biota to physical and chemical changes.

Projections of ocean biogeochemistry represent the open oceans rather well, but coastal and shelf regions only poorly. From a global perspective, open ocean NPP will decrease moderately by 2100 under both medium (SRES B1 or RCP4.5) and high emission scenarios (*medium confidence*; A2 or RCP6.0 to 8.5; Sections 6.3.4, 6.5.1), paralleled by an increase in NPP at high latitudes and a decrease in the tropics (*medium confidence*; Sections 6.3.4, 6.5.1; Box CC-PP).

Overall, the projected responses of marine organisms and ecosystems to climate change include changes in primary productivity (*medium confidence*), species' life history (*medium confidence*), distribution, abundance, and diversity across marine food webs (*high confidence*) in a time frame of 20 to 80 years from 2010, with substantially larger long-term (end of 21st century) responses under high emission scenarios (*high confidence*). These changes will be largest under business-as-usual scenarios (RCP8.5) and increase the vulnerability of human societies, by affecting income, employment, and food security through their effects on fisheries, tourism, and regulatory services such as coastal protection (*medium confidence*; Section 6.4.1.3; Box CC-CR).

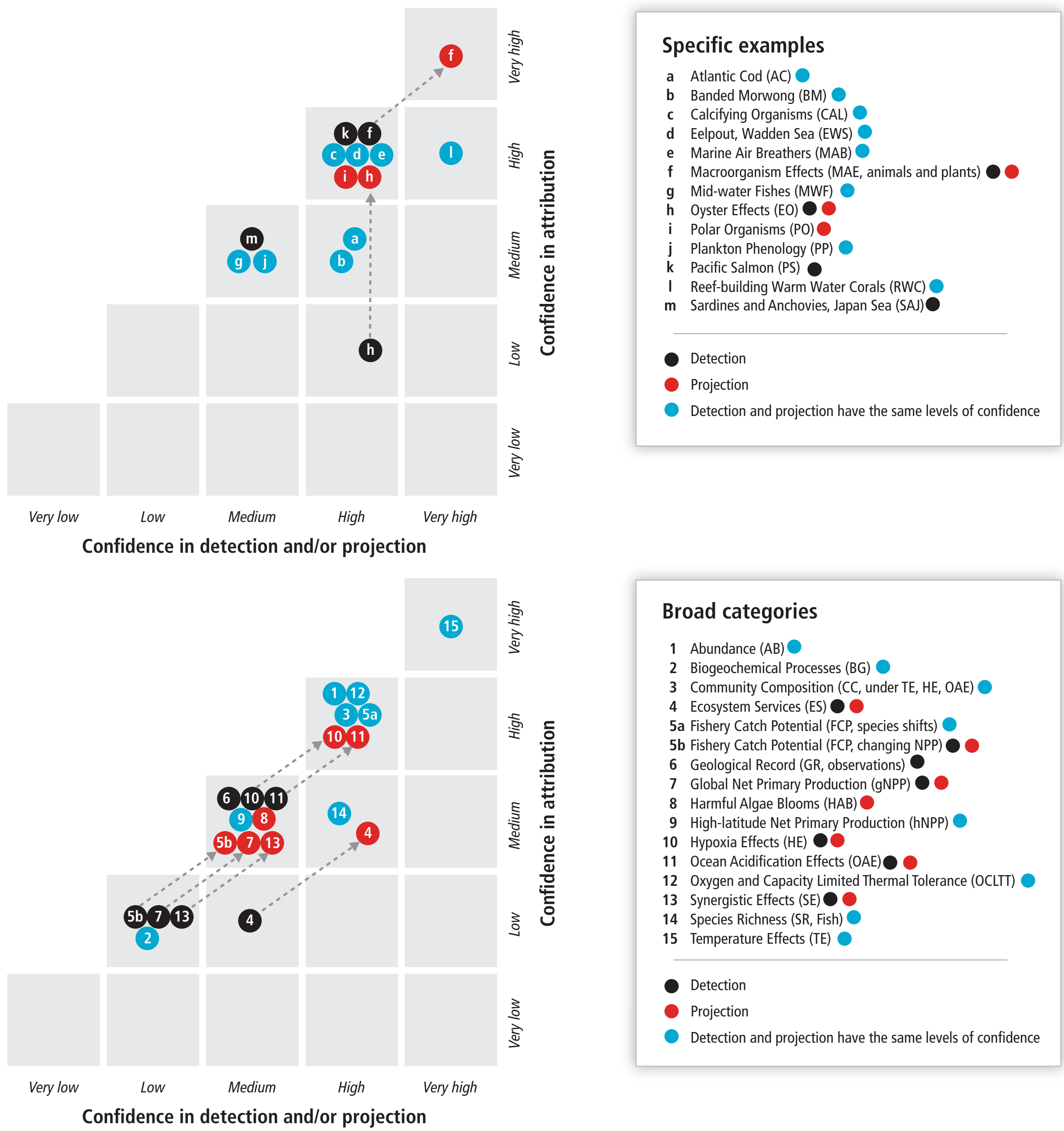


Figure 6-15 | Overview of the levels of confidence in detection, as well as in projection, of climate change effects on ocean systems, in relation to the levels of confidence in attributing these effects to the respective climate forcings. Case studies, processes, and concepts relevant in assessing the effects of climate change are represented by their acronyms in both text and figure. While confidence in the presence of effects is often high, the direct attribution to one driver in field experiments is difficult, as drivers are often highly correlated with each other (e.g., warming with changes in stratification, hence reduced nutrient supply). Some climate change impacts have been condensed into broad categories to avoid overpopulating the figures (e.g., Bio-Geochemical processes, BG). Note that the term "attribution" is used for both present-day detections in the field and future projections, the latter including qualitative and quantitative extrapolations and simulations of future conditions from fundamental principles, experiments, and models. Firm knowledge from experiments (field, laboratory, and modeling) simulating future conditions enhances the respective confidence levels to those for detection or projection. The empirical observations resulting from those experiments are directly attributable to the respective drivers. Confidence in attribution is enhanced if these experiments identify the underlying mechanisms and their responses. See text for the discussion of depicted examples and categories. Confidence assignments focus on the nature and size of effects, not on model capacity to quantify their magnitude reliably.

6.6. Chapter Conclusions and Key Uncertainties

This section provides an overview of confidence levels in the detection and projection of climate change effects on ocean systems, and of confidence levels in their attribution to different forcings. It distinguishes between effects previously observed and those projected, and considers confidence in the knowledge of underlying principles as discussed in this chapter. While the anthropogenic signal is conspicuous in the oceans (Section 6.1.1), clear attribution to anthropogenic influences on climate is not always possible in individual case studies, owing to the inherent variability of the system (Figure 6-15; acronyms of relevant processes, capitalized, link between text and figure).

Present-day observations and those from the Geological Record (GR; Figure 6-15) show similar signs of response to environmental changes, for example, warming at high CO_2 levels, and similar ecological consequences in the ocean (*robust evidence*, *medium agreement*; *medium confidence*). However, the ongoing rate of anthropogenic CO_2 release and hence ocean acidification is unprecedented in the last 65 Ma (*high confidence*) and probably the last 300 Ma (Section 6.1.2).

6.6.1. Key Risks Related to Climate Change: Constraints on Ecosystem Services

Empirical studies provide evidence that climate change has impacted marine ecosystems (*high confidence*; FAQ 6.4; Table 6-6) and has caused changes in provisioning, regulating, and supportive Ecosystem Services (ES; *medium confidence*). Climate change may also have affected cultural services (*limited evidence*, *medium agreement*) but attribution of impacts to these services remains a challenge (*low confidence*), owing to the intrinsic difficulties of assessing these services, the lack of long time-series data, and confounding human impacts. In light of available understanding of cause and effect of climate change impacts on marine ecosystems (*high confidence*), future climate change will affect some ecosystem services (*high confidence* in projection, *medium confidence* in attribution). Projected changes in the availability of marine resources and ecosystem services are expected to affect economics, human livelihood, and food security. Vulnerability is highest for the national economies of tropical coastal countries (*high confidence*).

6.6.1.1. Redistribution and Constraints on Microbial Functions and Primary Productivity

Laboratory and mesocosm studies have identified various microbially mediated processes responding to climate-induced changes in light, nutrient supply, temperature, CO_2, and hypoxia (*high confidence*). Such processes include nitrogen fixation and the nitrogen cycle, carbon sequestration and export production, calcification, respiration, O_2 production, climate-feedback by dimethylsulfide (DMS) production, and nutrient recycling. However, changes in these Bio-Geochemical processes (BG) in the field are difficult to detect, project, and attribute to climate change (*low confidence*; Sections 6.3.1-5).

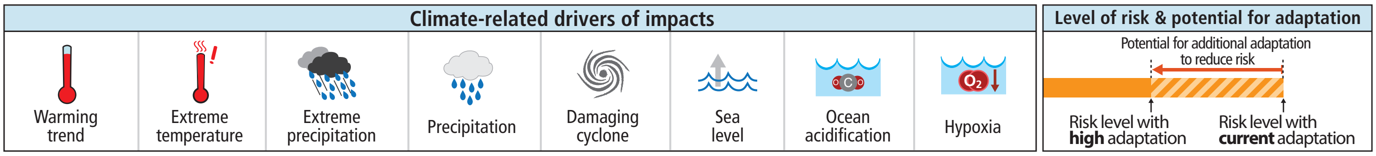
The trends in net primary production recently reported for much of the low-latitude ocean using satellite observations differ considerably from those few long-term direct estimates of NPP at oceanic time series sites (Sections 6.1.2, 6.3.4). Increased NPP at high latitudes (hNPP, detected and attributable to climate change with *medium confidence*; Section 6.3.4; Box CC-PP) are indicated by satellite images (*medium confidence*) and due to reduction and thinning of sea ice. Trends in NPP will be strengthened with further warming (*medium confidence*). Modeling projects that global NPP (gNPP) will decrease by 2100 under RCP scenarios (*medium confidence*; Section 6.5.1; Box CC-PP).

6.6.1.2. Warming-Induced Species Redistribution, Loss of Biodiversity, and Fisheries Catch Potential

Long-term observations show variability in oceanographic conditions with a key role of temperature and changing oceanographic regimes causing observed changes in ecosystem structure and fish stocks (*very high confidence*; cf. Section 30.7.1.1). Temperature Effects (TE) reflect the differential specialization of all life forms in limited ambient temperature ranges (*very high confidence*). Temperature exerts strong MAcroorganism Effects (MAE), that is, on animals and plants. Warming is presently causing and will cause species displacements and largely poleward shifts in biogeographic distribution of zooplankton and fishes, paralleled by altered seasonal activity, species abundance, migration, and body size (*high* to *very high confidence*; Section 6.3.1), and leading to shifts in Community Composition (CC; *high confidence*; Box 6-1). Causes and effects are understood for fishes and most invertebrates via their Oxygen and Capacity Limited Thermal Tolerance (OCLTT; *robust evidence*, *medium agreement*; *high confidence*; Section 6.3.1). Such knowledge supports projections into the future (*high confidence*; Section 6.5), which are influenced by the limited potential of organisms to adapt. Alterations in species ABundance (AB) result when organisms encounter shifting mean and extreme temperatures (*high confidence* in detection and attribution). Such trends will be exacerbated during future warming (*high confidence*; Section 6.5.1).

Among prominent examples, warming has caused and will cause northward shift and expansion of the geographic distribution of North Atlantic Cod (AC; *high confidence* in detection or projection, *medium confidence* in detection or projection and attribution; Section 6.3.1) and shifting growth patterns in relation to the distribution of Banded Morwong around New Zealand (BM; *high confidence* in detection or projection, *medium confidence* in detection or projection and attribution). Warming has shifted dominant species from Sardines to Anchovies in the Sea of Japan (SAJ; *medium confidence* in detection, *medium confidence* in detection and attribution; Sections 6.3.1, 6.3.6). Warming extremes have reduced and will further reduce the abundance of Eelpout in the Wadden Sea (EWS; *high confidence* in detection or projection, *high confidence* in detection or projection and attribution; Section 6.3.1). Extreme warming events increase mortalities of Pacific Salmon during spawning migrations (PS; *high confidence* in detection, *high confidence* in detection and attribution; Section 6.3.1) in Fraser River, Canada. At temperate and high latitudes, communities display increasing fish Species Richness (SR) resulting from latitudinal shifts of species and attributed to warming and loss of sea ice, although the relative contributions of regional climate variation and long-term global trends have not been quantified (*high confidence* in detection, *medium confidence* in detection and attribution; Sections 6.3.1, 6.5.2). Latitudinal species shifts are

Table 6-6 | Coastal and oceanic key risks from climate change and the potential for risk reduction through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as *very low*, *low*, *medium*, *high*, or *very high*. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080–2100), for global mean temperature increase of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols. Acronyms for oceans sub-regions are as follows: HLSBS = High-Latitude Spring Bloom Systems; EUS = Equatorial Upwelling Systems; SES = Semi-Enclosed Seas; CBS = Coastal Boundary Systems; EBUE = Eastern Boundary Upwelling Ecosystems; STG = Sub-Tropical Gyres, DS = Deep Sea (>1000 m).



Risks to ecosystems and adaptation options

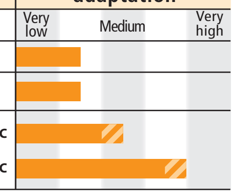
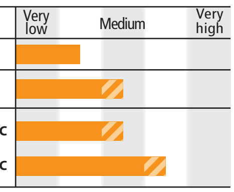
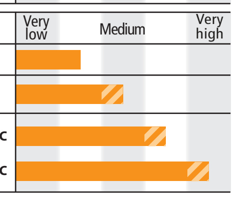
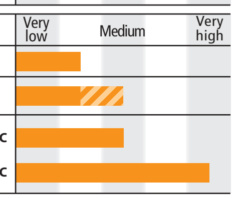
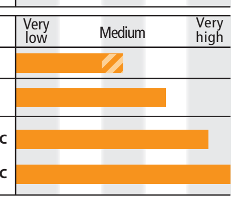
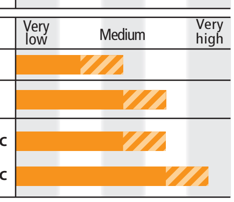
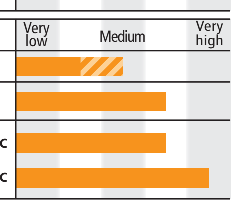
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Changes in ecosystem productivity associated with the redistribution and loss of net primary productivity in open oceans. (*medium confidence*) [6.5.1, 6.3.4, 30.5.1-2, Box CC-PP]	Adaptation options are limited to the translocation of industrial fishing activities due to regional decreases (low latitude) versus increases (high latitude) in productivity, or to the expansion of aquaculture.	Warming trend; Extreme temperature	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Distributional shift in fish and invertebrate species, fall in fisheries catch potential at low latitudes, e.g., in EUS, CBS, and STG regions. (*high confidence*) [6.3.1, 6.5.2-3, 30.5.1-4, 30.6.2, Box CC-MB]	Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their changes in distribution to maintain temperatures. Human adaptation options involve the large-scale translocation of industrial fishing activities following the regional decreases (low latitude) versus (possibly transient) increases (high latitude) in catch potential as well as deploying flexible management that can react to variability and change. Further options include improving fish resilience to thermal stress by reducing other stressors such as pollution and eutrophication, the expansion of sustainable aquaculture and development of alternative livelihoods in some regions.	Warming trend; Extreme temperature	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
High mortalities and loss of habitat to larger fauna including commercial species due to hypoxia expansion and effects. (*high confidence*) [6.3.3, 30.5.3-5]	Human adaptation options involve the large-scale translocation of industrial fishing activities as a consequence of the hypoxia-induced decreases in biodiversity and fisheries catch of pelagic fish and squid. Special fisheries may benefit (Humboldt squid). Reducing the amount of organic carbon running off coastlines by controlling nutrients and pollution running off agricultural areas can reduce microbial activity and consequently limit the extent of the oxygen drawdown and the formation of coastal dead zones.	Warming trend; Hypoxia; Precipitation; Extreme precipitation	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Ocean acidification: Reduced growth and survival of commercially valuable shellfish and other calcifiers, e.g., reef building corals, calcareous red algae. (*high confidence*) [5.3.3.5, 6.1.1, 6.3.2, 6.4.1.1, 30.3.2.2, Box CC-OA]	Evidence for differential resistance and evolutionary adaptation of some species exists but is likely limited by the CO_2 concentrations and high temperatures reached; adaptation options include the shift to exploiting more resilient species or the protection of habitats with low natural CO_2 levels, as well as the reduction of other stresses, mainly pollution and limiting pressures from tourism and fishing.	Ocean acidification	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Reduced biodiversity, fisheries abundance and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, exacerbated by ocean acidification, e.g., in CBS, SES, and STG regions. (*high confidence*) [5.4.2.4, 6.3.1, 6.4.2, 30.3.1.1, 30.3.2.2, 30.5.3-6, Box CC-CR]	Evidence of rapid evolution by corals is very limited or nonexistent. Some corals may migrate to higher latitudes. However, the movement of entire reef systems is unlikely given estimates that they need to move at the speed of 10 – 20 km yr^{-1}. Human adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing. This option will delay the impacts of climate change by a few decades but is likely to disappear as thermal stress increases.	Warming trend; Damaging cyclone; Extreme temperature; Ocean acidification	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Coastal inundation and habitat loss due to sea level rise, extreme events, changes in precipitation, and reduced ecological resilience, e.g., in CBS and STG subregions. (*medium to high confidence*) [5.4.2.3-7, 5.5.2, 5.5.4, 30.5.6, Box CC-CR]	Options to maintain ecosystem integrity are limited to the reduction of other stresses, mainly pollution and limiting pressures from tourism, fishing, physical destruction, and unsustainable aquaculture; reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients; increased mangrove, coral reef, and seagrass protection and restoration to protect numerous ecosystem goods and services such as coastal protection, tourist value, and fish habitat.	Warming trend; Sea level; Ocean acidification; Extreme precipitation; Damaging cyclone	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Marine biodiversity loss with high rate of climate change. (*medium confidence*) [6.3.1-3, 6.4.1.2-3, Table 30.4, Box CC-MB]	Adaptation options are limited to the reduction of other stresses, mainly to reducing pollution and to limiting pressures from tourism and fishing.	Warming trend; Extreme temperature; Ocean acidification	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	

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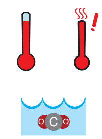
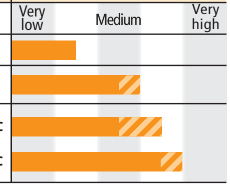
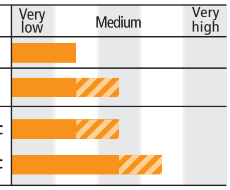
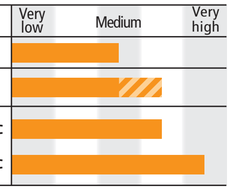
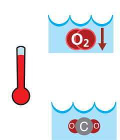
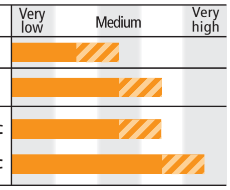
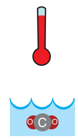
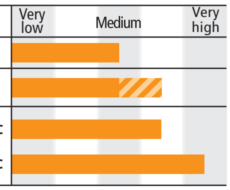
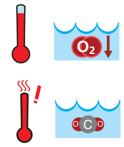
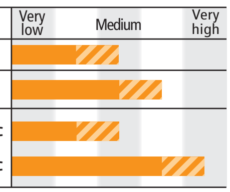
Table 6-6 (continued)

Risks to fisheries				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Decreased production of global shellfish fisheries. (*high confidence*) [6.3.2, 6.3.5, 6.4.1.1, 30.5.5, 30.6.2.1, Box CC-OA]	Effective shift to alternative livelihoods, changes in food consumption patterns, and adjustment of (global) markets.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Global redistribution and decrease of low-latitude fisheries yields are paralleled by a global trend to catches having smaller fishes. (*medium confidence*) [6.3.1, 6.4.1, 6.5.3, 30.5.4, 30.5.6, 30.6.2]	Increasing coastal poverty at low latitudes as fisheries becomes smaller – partially compensated by the growth of aquaculture and marine spatial planning, as well as enhanced industrialized fishing efforts.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Redistribution of catch potential of large pelagic-highly migratory fish resources, such as tropical Pacific tuna fisheries. (*high confidence*) [6.3.1, 6.4.3, Table 30.4]	International fisheries agreements and instruments, such as the tuna commissions, may have limited success in establishing sustainable fisheries yields.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Variability of small pelagic fishes in Eastern Boundary Upwelling systems is becoming more extreme at interannual to multi-decadal scales, making industry and management decisions more uncertain. (*medium confidence*) [6.3.2, 6.3.3, 30.5.5, Box CC-UP]	Development of new and specific management tools and models may have limited success to sustain yields. Reduction in fishing intensity increases resilience of the fisheries.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Decrease in catch and species diversity of fisheries in tropical coral reefs, exacerbated by interactions with other human drivers such as eutrophication and habitat destruction. (*high confidence*) [6.4.1, 30.5.3-4, 30.5.6, Table 30-4, Box CC-CR]	Restoration of overexploited fisheries and reduction of other stressors on coral reefs delay ecosystem changes. Human adaptation includes the usage of alternative livelihoods and food sources (e.g., coastal aquaculture).		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Current spatial management units, especially the MPAs, may fail in the future due to shifts in species distribution and community structure. (*high confidence*) [6.3.1, 6.4.2.1, 30.5.1, Box CC-MB]	Continuous revision and shifts of MPA borders, and of MPA goals and performance.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

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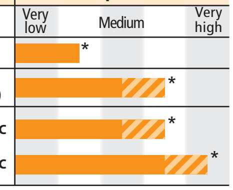
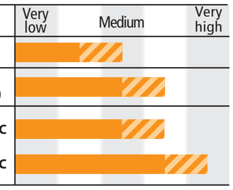
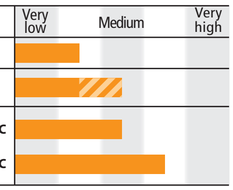
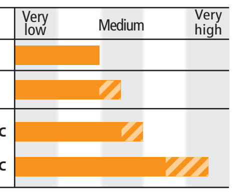
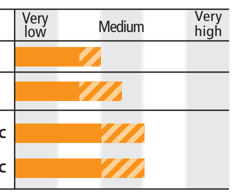
projected to continue in the 21st century under all IPCC emission scenarios (*high confidence*; Sections 6.3.1, 6.3.5, 6.3.7, 6.4.1, 6.5.2).

Climate-induced regime shifts and regional changes in Plankton Phenology (PP; *medium confidence*) have caused and will cause changes in food composition and availability to animals. Species shifts and changing species composition lead to changes in Fishery Catch Potential (FCP; *high confidence*; 5a in Figure 6-15), partly attributable to climate change (*high confidence*) and to sustained fishing pressure (Section 6.5.3). Fisheries Catch Potentials (FCP) will be redistributed, decrease at low latitudes, and increase at high latitudes (*high confidence*; 5a in Figure 6-15). These trends will possibly be strengthened by the projected decrease in NPP at low latitudes and increase in NPP at high latitudes (*medium confidence*; Sections 6.5.2-3; 5b in Figure 6-15). Polar Organisms (PO) that are unable to migrate to cooler waters, and to acclimatize or to adapt to warming, will become marginalized, contributing to the projected high species turnover in polar areas (*high confidence*; Sections 6.3.1, 6.5.2).

Detected effects on Marine Air Breathers (MAB: mammals, seabirds, and reptiles) include changing abundances and phenology, shifts in species distribution, and in sea turtle sex ratios (*high confidence*), all of which are partly attributed to climate change (*high confidence*). However, few effects are directly linked to climate drivers (e.g., temperature-driven turtle sex ratio); most effects are due to shifts in habitat structure (e.g., loss of sea ice), changing availability of prey organisms, or changes in

Table 6-6 (continued)

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Risks to humans and infrastructure				
Coastal socioeconomic security. (*high confidence*) [5.5.2, 5.5.4, 30.6.5, 30.7.1, Table 30-4]	Human adaptation options involve (1) protection using coastal defences (e.g. seawalls) and soft measures (e.g., mangrove replanting and enhancing coral growth); (2) accommodation to allow continued occupation of coastal areas by making changes to human activities and infrastructure; and (3) managed retreat as a last viable option. Options vary from large-scale engineering works to smaller scale community projects. Options are available under the more traditional CZM (coastal zone management) framework but increasingly under DRR (disaster risk reduction) and CCA (climate change adaptation) frameworks.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
	**High confidence* in existence of adaptation measures, *Low confidence* in magnitude of risk reduction			
Reduced livelihoods and increased poverty. (*medium confidence*) [6.4.1-2, 30.6.2, 30.6.5]	Human adaptation options involve the large-scale translocation of industrial fishing activities following the regional decreases (low latitude) versus increases (high latitude) in catch potential and shifts in biodiversity. Artisanal local fisheries are extremely limited in their adaptation options by available financial resources and technical capacities, except for their potential shift to other species of interest.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Impacts due to increased frequency of harmful algal blooms (*medium confidence*) [6.4.2.3, 30.6.3]	Adaptation options include improved monitoring and early warning system, reduction of stresses favoring harmful algal blooms, mainly pollution and eutrophication, as well as the avoidance of contaminated areas and fisheries products.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Impacts on marine resources threatening regional security as territorial disputes and food security challenges increase (*limited evidence, medium agreement*) [AR5 SREX, 30.6.5, 30.7.2, 12.4-6, 29.3]	Decrease in marine resources, movements of fish stocks and opening of new seaways , and impacts of extreme events coupled with increasing populations will increase the potential for conflict in some regions, drive potential migration of people, and increase humanitarian crises.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Impacts on shipping and infrastructure for energy and mineral extraction increases as storm intensity and wave height increase in some regions (e.g., high latitudes) (*high confidence*) [AR5 SREX, 30.6.2.3-4, 30.6.5, 29.3]	Adaptation options are to limit activities to particular times of the year and/or develop strategies to decrease the vulnerability of structures and operations.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

foraging efficiency, in both mammals (polar bears, walruses) and birds (penguins, albatrosses). Such trends will be exacerbated by future warming (*high confidence*; Sections 6.3.7, 6.5.2).

6.6.1.3. Expanding Hypoxia Affecting Marine Resources

Hypoxic zones in marine sediments and pelagic OMZs will continue to expand in the future, owing to climate-induced warming trends (Section 6.1.1). Local and regional Hypoxia Effects (HE) have been observed (*medium confidence*) and will be exacerbated in the future (*high confidence*; Section 6.3.3) causing habitat loss for groundfishes and pelagic predators and affecting the distribution of key zooplankton and nekton species (*medium confidence*). Progressive hypoxia is causing shifts in community composition toward hypoxia-tolerant species, excluding calcifiers due to elevated pCO_2 (*high confidence*), benefiting specialized microbes, and leading to reduced biodiversity and the loss of higher life forms (*high confidence*; Section 6.3.3). Loss of deep habitat and biomass of Mid-Water Fishes (MWF; Section 6.3.3; *medium confidence* in detection) off California is also attributed to hypoxia (*medium confidence*). These trends will continue into the future (*medium confidence*).

6.6.1.4. Constraints on Marine Calcifiers and Associated Fisheries and Aquaculture due to Ocean Acidification

Ocean acidification will exert negative effects on species and whole ecosystems and their services, especially those relying on carbonate structures such as warm-water coral reefs (*high confidence*; cf. Section 30.7.1.2). Presently, only a small number of field observations have detected Ocean Acidification Effects (OAE; *medium confidence*), but experiments and natural analogs support reliable but qualitative projections and attribution (*high confidence*). A specific glimpse into the future of anthropogenic OA is provided by negative Effects of upwelled CO_2-rich waters on Pacific Oysters (EO) introduced to aquaculture along the North American west coast (*high confidence* in detection, *low confidence* in attribution to anthropogenic causes). Findings in experimental laboratory and field studies as well as at natural analogs support attribution of projected effects to future CO_2

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concentrations (*medium confidence*), with species-specific sensitivities across phyla (*high confidence*). Projected effects are most harmful to strong CALcifiers (CAL; *high confidence*), for example, some echinoderms, bivalves, gastropods, warm-water corals, and crustose algae, and less harmful to some crustaceans and, possibly, fishes. Projections from experimental studies and observations at natural analogs indicate shifts in Community Composition (CC) to more active animals and from calcifiers (CAL) to non-calcifiers in all organism groups (*high confidence* in both projection and attribution to increased CO_2; Section 6.3.2; Table 6-3).

6.6.1.5. Interactions of Climate-Related Drivers Exacerbating Impacts on Organisms, Ecosystems, and Their Services

Climate change involves interactions of temperature with other climate-related drivers and their effects (ocean acidification, hypoxia, freshening, nutrient supply, organism shifts resulting in changing interactions between species, changes in habitat structure, e.g., loss of sea ice). Strong interactions with other human impacts like eutrophication, fishing, and other forms of harvesting accelerate and amplify climate-induced changes (*high confidence*; Section 6.3.5, 30.7.1.1). Harmful algal blooms (HAB) will be stimulated by warming, nutrient fluctuations in upwelling areas, eutrophication in coastal areas (Table 6-6), ocean acidification, and enhanced surface stratification (*medium confidence*). Synergistic Effects (SE) will be exacerbated in the future (*medium confidence*), but have not yet been clearly detected and attributed in the field (*low confidence*). For projected future effects, attribution of observed impacts to such synergisms is supported by experimental evidence, especially in animals and plants (*medium confidence*).

Increased bleaching and decreased calcification displayed by several Reef-building Warm-water Corals (RWC; *very high confidence*) over the last 3 decades are attributed to the ongoing warming trend, and the associated rise in extreme temperature events and amplitudes (*high confidence*; Sections 6.3.1, 30.5.6; Box CC-CR). Such trends will be exacerbated by future warming and synergistic effects (*high confidence*; cf. Section 30.5.4.2), with some amelioration by latitudinal shifts and evolutionary adaptation (Section 6.3.1; *low confidence*). Ocean acidification will have an increasing influence on reefs (*high confidence*), as indicated by similar phenomena during mass extinctions in Earth history.

6.6.2. Key Uncertainties

Key uncertainties result from insufficient knowledge of ocean systems. International organizations (both inter- and non-governmental) have the opportunity to play a key role in coordinating research concepts and approaches, working toward a coherent picture of climate change effects on the global ocean. Countries around the world have limited capacity and infrastructure to study the ocean's response to climate change. Long-term observational time series are especially lacking, in both quantity and quality. Research has provided valuable insights, but a unifying approach addressing principles across organism domains and ecosystems is still missing. Processes investigated so far differ largely by study organisms (plants, animals, phytoplankton, and bacteria) and by level of organization (ecosystem, whole organism, tissue, cell, molecular). Especially for microbes, available data are patchy and reported trends are often in different directions, partly due to different experimental protocols and/or over-reliance on species or strains of microbes that are readily culturable, and hence have been used for decades in laboratory research. The knowledge base of climate impacts on species, strains, or communities in the field is insufficient. Scaling from physiological studies on individual species to ecosystem changes has been successful in individual cases but has not been widely implemented, for example, to shifts in species interactions or food webs. An integrated framework of climate sensitivity at the ecosystem level that considers multiple drivers and their interactive effects needs to be developed further. This includes an in depth understanding of ecosystem structure (physical and biological) and functioning, of ecosystem complexity and species interactions, and of the resulting implications for biogeochemical processes. For all climate drivers, especially ocean warming, acidification, and hypoxia, studies integrating mechanistic knowledge and evolutionary adaptation over generations are needed. Research should also cover various climate zones and biomes. Laboratory and modeling experiments are needed to test hypotheses building on long-term field observations and observations at natural or paleo-analogs. Models should better integrate observations and mechanism-based understanding, and better project future interactions between human and natural systems in a changing climate.

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7

Food Security and Food Production Systems

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Executive Summary

The effects of climate change on crop and terrestrial food production are evident in several regions of the world (*high confidence*). Negative impacts of climate trends have been more common than positive ones. {Figures 7-2, 7-7} Positive trends are evident in some high-latitude regions (*high confidence*). Since AR4, there have been several periods of rapid food and cereal price increases following climate extremes in key producing regions, indicating a sensitivity of current markets to climate extremes, among other factors. {Figure 7-3, Table 18-3} Several of these climate extremes were made more likely as the result of anthropogenic emissions (*medium confidence*). {Table 18-3}

Climate trends are affecting the abundance and distribution of harvested aquatic species, both freshwater and marine, and aquaculture production systems in different parts of the world. {7.2.1.2, 7.3.2.4, 7.4.2} These are expected to continue with negative impacts on nutrition and food security for especially vulnerable people, particularly in some tropical developing countries {7.3.3.2}, but with benefits in other regions that become more favorable for aquatic food production (*medium confidence*). {7.5.1.1.2}

Studies have documented a large negative sensitivity of crop yields to extreme daytime temperatures around 30°C. {WGII AR4 Chapter 5, 7.3.2.1} These sensitivities have been identified for several crops and regions and exist throughout the growing season (*high confidence*). Several studies report that temperature trends are important for determining both past and future impacts of climate change on crop yields at sub-continental to global scales (*medium confidence*). {7.3.2, Box 7-1} At scales of individual countries or smaller, precipitation projections remain important but uncertain factors for assessing future impacts (*high confidence*). {7.3.2, Box 7-1}

Evidence since AR4 confirms the stimulatory effects of carbon dioxide (CO_2) in most cases and the damaging effects of elevated tropospheric ozone (O_3) on crop yields (*high confidence*). Experimental and modeling evidence indicates that interactions between CO_2 and O_3, mean temperature and extremes, water, and nitrogen are nonlinear and difficult to predict (*medium confidence*). {7.3.2.1, Figure 7-2}

Changes in climate and CO_2 concentration will enhance the distribution and increase the competitiveness of agronomically important and invasive weeds (*medium confidence*). Rising CO_2 may reduce the effectiveness of some herbicides (*low confidence*). The effects of climate change on disease pressure on food crops are uncertain, with evidence pointing to changed geographical ranges of pests and diseases but less certain changes in disease intensity (*low confidence*). {7.3.2.3}

All aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (*high confidence*). {7.3.3.1, Table 7-1} There remains limited quantitative understanding of how non-production elements of food security will be affected, and of the adaptation possibilities in these domains. Nutritional quality of food and fodder, including protein and micronutrients, is negatively affected by elevated CO_2, but these effects may be counteracted by effects of other aspects of climate change (*medium confidence*). {7.3.2.5}

For the major crops (wheat, rice, and maize) in tropical and temperate regions, climate change without adaptation will negatively impact production for local temperature increases of 2°C or more above late-20th-century levels, although individual locations may benefit (*medium confidence*). {7.4, Figure 7-4} Projected impacts vary across crops and regions and adaptation scenarios, with about 10% of projections for the period 2030–2049 showing yield gains of more than 10% and about 10% of projections showing yield losses of more than 25%, compared to the late 20th century. {Figure 7-5} After 2050, the risk of more severe impacts increases. {Figure 7-5} Regional Chapters 22 (Africa), 23 (Europe), 24 (Asia), 27 (Central and South America), and Box 7-1 show crop production to be consistently and negatively affected by climate change in the future in low-latitude countries, while climate change may have positive or negative effects in northern latitudes (*high confidence*). Climate change will increase progressively the inter-annual variability of crop yields in many regions (*medium confidence*). {Figure 7-6}

On average, agronomic adaptation improves yields by the equivalent of ~15-18% of current yields {Figure 7-8, Table 7-2}, but the effectiveness of adaptation is highly variable (*medium confidence*) ranging from potential dis-benefits to negligible to very substantial (*medium confidence*). {7.5.1.1.1} Projected benefits of adaptation are greater for crops in temperate, rather than tropical, regions (*medium confidence*) {7.5.1.1.1, Figures 7-4, 7-7}, with wheat- and rice-based systems more adaptable than those of maize (*low confidence*). {Figure 7-4} Some adaptation options are more effective than others (*medium confidence*). {Table 7-2}

Global temperature increases of ~4°C or more above late-20th-century levels, combined with increasing food demand, would pose large risks to food security globally and regionally (*high confidence*). Risks to food security are generally greater in low-latitude areas. {Box 7-1, Table 7-3, Figures 7-4, 7-5, 7-7}

Changes in temperature and precipitation, without considering effects of CO_2, will contribute to increased global food prices by 2050, with estimated increases ranging from 3 to 84% (*medium confidence*). Projections that include the effects of CO_2 changes, but ignore O_3 and pest and disease impacts, indicate that global price increases are about *as likely as not*, with a range of projected impacts from –30% to +45% by 2050. {7.4.4}

Adaptation in fisheries, aquaculture, and livestock production will potentially be strengthened by adoption of multi-level adaptive strategies to minimize negative impacts. Key adaptations for fisheries and aquaculture include policy and management to maintain ecosystems in a state that is resilient to change, enabling occupational flexibility, and development of early warning systems for extreme events (*medium confidence*). {7.5.1.1.2} Adaptations for livestock systems center on adjusting management to the available resources, using breeds better adapted to the prevailing climate and removing barriers to adaptation such as improving credit access (*medium confidence*). {7.5.1.1.3}

A range of potential adaptation options exist across all food system activities, not just in food production, but benefits from potential innovations in food processing, packaging, transport, storage, and trade are insufficiently researched. {7.1, 7.5, 7.6, Figures 7-1, 7-7, 7-8} More observational evidence is needed on the effectiveness of adaptations at all levels of the food system. {7.6}

7.1. Introduction and Context

Many definitions of food security exist, and these have been the subject of much debate. As early as 1992, Maxwell and Smith (1992) reviewed more than 180 items discussing concepts and definitions, and more definitions have been formulated since (DEFRA, 2006). Whereas many earlier definitions centered on food production, more recent definitions highlight access to food, in keeping with the 1996 World Food Summit definition (FAO, 1996) that food security is met when "all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life." Worldwide attention on food access was given impetus by the food "price spike" in 2007–2008, triggered by a complex set of long- and short-term factors (FAO, 2009b; von Braun and Torero, 2009). FAO concluded, "provisional estimates show that, in 2007, 75 million more people were added to the total number of undernourished relative to 2003–05" (FAO, 2008); this is arguably a low-end estimate (Headey and Fan, 2010). More than enough food is currently produced per capita to feed the global population, yet about 870 million people remained hungry in the period from 2010 to 2012 (FAO et al., 2012). The questions for this chapter are how far climate and its change affect current food production systems and food security and the extent to which they will do so in the future (Figure 7-1).

7.1.1. Food Systems

A food system is all processes and infrastructure involved in satisfying a population's food security, that is, the gathering/catching, growing, harvesting (production aspects), storing, processing, packaging, transporting, marketing, and consuming of food, and disposing of food waste (non-production aspects). It includes food security outcomes of these activities related to availability and utilization of, and access to, food as well as other socioeconomic and environmental factors (Ericksen, 2008; Ericksen et al., 2010; Ingram, 2011). This chapter synthesizes and evaluates evidence for the impacts of climate on both production and non-production elements and their adaptation to climate change (Figure 7-1).

The impacts of climate change on food systems are expected to be widespread, complex, geographically and temporally variable, and profoundly influenced by socioeconomic conditions (Vermeulen et al., 2012). Changes in food system drivers give rise to changes in food security outcomes (*medium evidence*, *high agreement*), but often researchers consider only the impacts on the food production element of food security (Figure 7-1). Efforts to increase food production are nevertheless increasingly important as 60% more food will be needed by 2050 given current food consumption trends and assuming no significant reduction in food waste (FAO et al., 2012).

7.1.2. The Current State of Food Security

Most people on the planet currently have enough food to eat. The vast majority of undernourished people live in developing countries (*medium evidence*, *medium agreement*), when estimated based on aggregate national calorie availability and assumptions about food distribution and nutritional requirements. More precise estimates are possible with detailed household surveys, which often show a higher incidence of food insecurity than estimated by FAO. Using food energy deficit as the measure of food insecurity, Smith et al. (2006) estimated average rates of food insecurity of 59% for 12 African countries, compared to a 39% estimate from FAO for the same period (Smith et al., 2006). While there is *medium evidence*, *medium agreement* on absolute numbers, there is *robust evidence*, *high agreement* that sub-Saharan Africa has the highest proportion of food-insecure people, with an estimated regional average of 26.8% of the population undernourished in 2010–2012, and where rates higher than 50% can be found (FAO et al., 2012). The largest numbers of food-insecure persons are found in South Asia, which has roughly 300 million undernourished (FAO et al., 2012). In addition to common measures of calorie availability, food security can be broadened to include nutritional aspects based on the diversity of diet including not only staple foods but also vegetables, fruits, meat, milk, eggs, and fortified foods (FAO, 2011). There is *robust evidence* and *high agreement* that lack of essential micronutrients such as zinc and vitamin A affect hundreds of millions of additional people (Lopez et al., 2006; Pinstrup-Andersen, 2009).

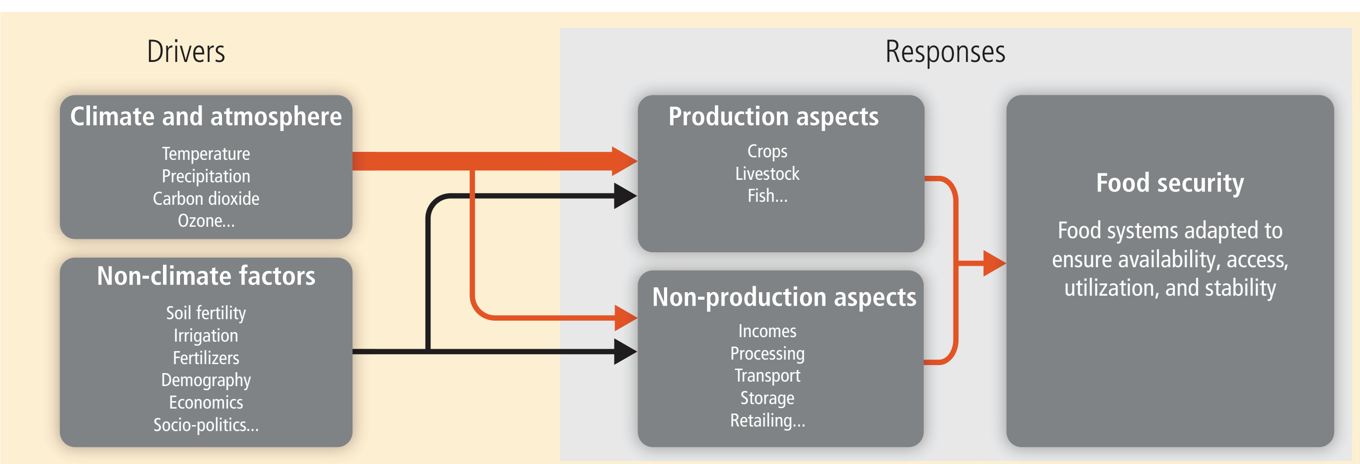


Figure 7-1 | Main issues of the chapter. Drivers are divided into climate and non-climate elements, affecting production and non-production elements of food systems, thereafter combining to provide food security. The thickness of the red lines is indicative of the relative availability of refereed publications on the two elements.

Food insecurity is closely tied to poverty; globally about 25 to 30% of poor people, measured using a US$1 to US$2 per day standard, live in urban areas (Ravallion et al., 2007; IFAD, 2010). Most poor countries have a larger fraction of people living in rural areas and poverty rates tend to be higher in rural settings (by slight margins in South Asia and Africa, and by large margins in China). In Latin America, poverty is more skewed to urban areas, with roughly two-thirds of the poor in urban areas, a proportion that has been growing in the past decade (*medium evidence*, *medium agreement*). Rural areas will continue to have the majority of poor people for at least the next few decades, even as population growth is higher in urban areas (*medium evidence*, *medium agreement*) (Ravallion et al., 2007; IFAD, 2010).

The effects of price volatility are distinct from the effects of gradual price rises, for two main reasons. First, rapid shifts make it difficult for the poor to adjust their activities to favor producing higher value items. Second, increased volatility leads to greater uncertainty about the future and can dampen willingness to invest scarce resources into productivity enhancing assets, such as fertilizer purchases in the case of farmers or rural infrastructure in the case of governments. Several factors have been found to contribute to increased price volatility: poorly articulated local markets, increased incidence of adverse weather events, and greater reliance on production areas with high exposure to such risks, biofuel mandates, and increased links between energy and agricultural markets (World Bank, 2012). Vulnerability to food price volatility depends on the degree to which households and countries are net food purchasers; the level of integration into global, regional, and local markets; and their relative degree of volatility, which in turn is conditional on their respective governance (*robust evidence*, *medium agreement*) (HLPE, 2011; World Bank, 2012).

7.1.3. Summary from AR4

Food systems as integrated drivers, activities, and outcomes for food security did not feature strongly in AR4. Summary points from AR4 were that, with *medium confidence*, in mid- to high-latitude regions moderate warming will raise crop and pasture yields. Sight warming will decrease yields in low-latitude regions. Extreme climate and weather events will, with *high confidence*, reduce food production. The benefits of adaptation vary with crops and across regions and temperature changes; however, on average, they provide approximately a 10% yield benefit when compared with yields when no adaptation is used (WGII AR4 Section 5.5.1). Adaptive capacity is projected to be exceeded in low-latitude areas with temperature increases of more than 3°C. Local extinctions of particular fish species are expected at the edges of their ranges (*high confidence*) and have serious negative impacts on fisheries (*medium confidence*).

7.2. Observed Impacts, with Detection and Attribution

7.2.1. Food Production Systems

Formal detection of impacts requires that observed changes be compared to a clearly specified baseline that characterizes behavior in the absence of climate change (Chapter 18). For food production systems, the number and strength of non-climate drivers, such as cultivar improvement or increased use of irrigation and fertilizers in the case of crops, make defining a clear baseline extremely difficult. Most non-climatic factors are not very well characterized in terms of spatial and temporal distributions, and the relationships between these factors and specific outcomes of interest (e.g., crop or fish production) are often difficult to quantify.

Attribution of any observed changes to climate trends are further complicated by the fact that models linking climate and agriculture must, implicitly or explicitly, make assumptions about farmer behavior. In most cases, models implicitly assume that farming practices or technologies did not adjust in response to climate over the period of interest. This assumption can be defended in some cases based on ancillary data on practices, or based on small differences between using models with and without adaptation (Schlenker and Roberts, 2009). However, in some instances the relationship between climate conditions and crop production has been shown to change over time because of management changes, such as introduction of irrigation or changes in crop varieties (Zhang et al, 2008; Liu et al., 2009; Sakurai et al., 2012).

7.2.1.1. Crop Production

Many studies of cropping systems have estimated impacts of observed climate changes on crop yields over the past half century, although they typically do not attempt to compare observed yields to a counterfactual baseline, and thus are not formal detection and attribution studies. These studies employ both mechanistic and statistical approaches (Section 7.3.1), and estimate impacts by running the models with observed historical climate and then computing trends in modeled outcomes. Based on these studies, there is *medium confidence* that climate trends have negatively affected wheat and maize production for many regions (Figure 7-2) (*medium evidence*, *high agreement*). Because many of these regional studies are for major producers, and a global study (Lobell et al., 2011a) estimated negative impacts on these crops, there is also *medium confidence* for negative impacts on global aggregate production of wheat and maize. Effects on rice and soybean yields have been small in major production regions and globally (Figure 7-2) (*medium evidence*, *high agreement*). There is also *high confidence* that warming has benefitted crop production in some high-latitude regions, such as northeast China or the UK (Jaggard et al., 2007; Chen et al., 2010; Supit et al., 2010; Gregory and Marshall, 2012).

More difficult to quantify with models is the impact of very extreme events on cropping systems, as by definition these occur very rarely and models cannot be adequately calibrated and tested. Table 18-3 lists some notable extremes over the past decade, and the impacts on cropping systems. Despite the difficulty of modeling the impacts of these events, they clearly have sizable impacts (Sanchez et al. 2014) that are apparent immediately or soon after the event, and therefore not easily confused with effects of more slowly moving factors. For a subset of these events, climate research has evaluated whether anthropogenic activity has increased or decreased their likelihood (Table 18-3).

A sizable fraction of crop modeling studies were concerned with production for individual sites or provinces, spatial scales below which

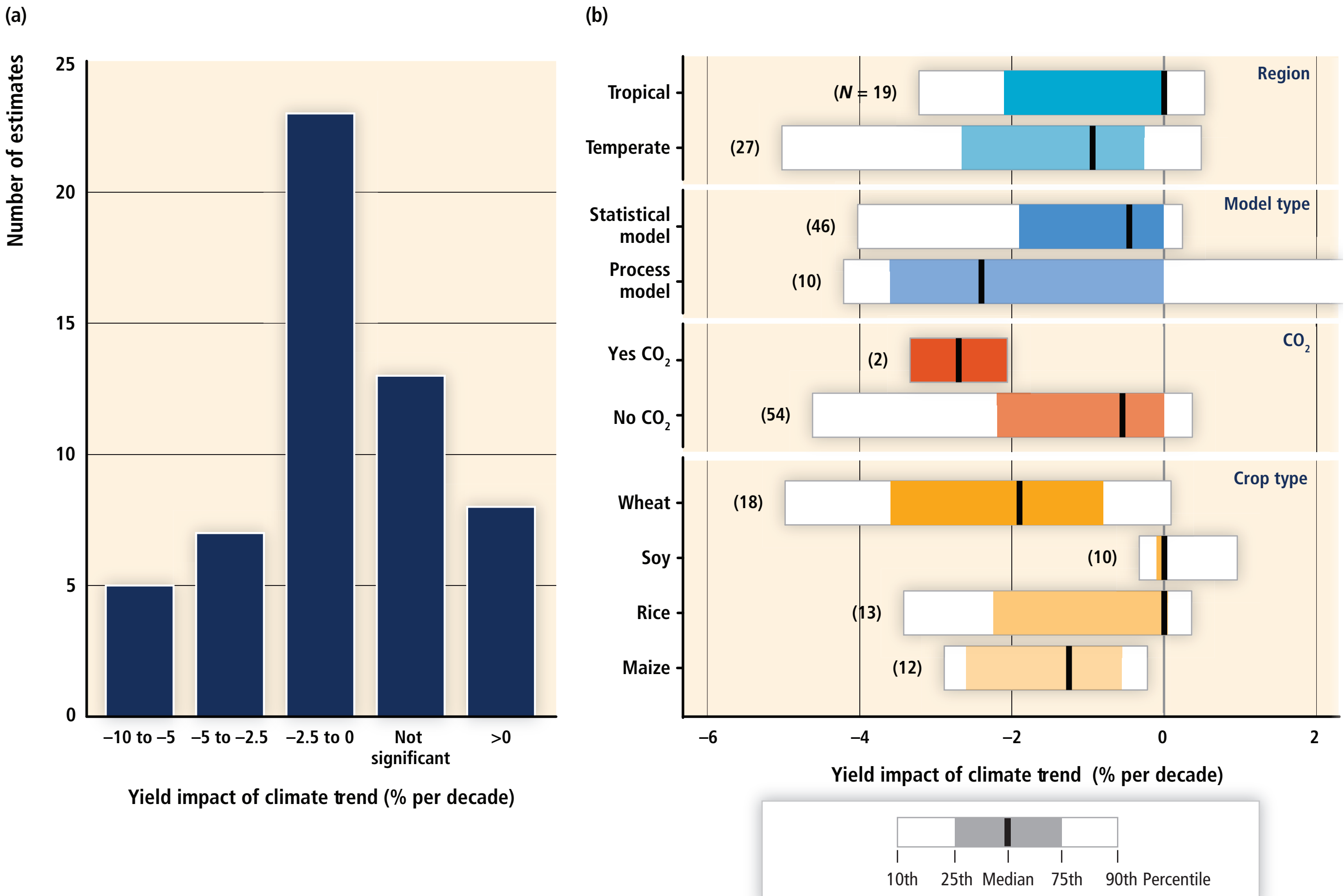


Figure 7-2 | Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive carbon dioxide (CO_2) trends (Section 7.3.2.1.2) but most did not. (a) Number of estimates with different level of impact (% yield per decade). (b) Boxplot of estimates separated by temperate vs. tropical regions, modeling approach (process-based vs. statistical), whether CO_2 effects were included, and crop. Boxplots indicate the median (vertical line), 25th to 75th percentiles (colored box), and 10th to 90th percentiles (white box) for estimated impacts in each category, and numbers in parentheses indicate the number of estimates. Studies were for China (Tao et al., 2006, 2008a, 2012; Wang et al., 2008; You et al., 2009; Chen et al., 2010), India (Pathak et al., 2003; Auffhammer et al., 2012), USA (Kucharik and Serbin, 2008), Mexico (Lobell et al., 2005), France (Brisson et al., 2010; Licker et al., 2013), Scotland (Gregory and Marshall, 2012), Australia (Ludwig et al., 2009), Russia (Licker et al., 2013), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Welch et al., 2010; Lobell et al., 2011a). Values from all studies were converted to percentage yield change per decade. Each study received equal weighting as insufficient information was available to judge the uncertainties of each estimate.

the changes in climate conditions are attributable to anthropogenic activity (WGI AR5 Chapter 10). Similarly, most crop studies have focused on the past few decades, a time scale shorter than most attribution studies for climate. However, some focused on continental or global scales (Lobell and Field, 2007; You et al., 2009; Lobell et al., 2011a), at which trends in several climatic variables, including average summer temperatures, have been attributed to anthropogenic activity. In particular, global temperature trends over the past few decades are attributable to human activity (WGI AR5 Chapter 10), and the studies discussed above indicate that this warming has had significant impacts on global yield trends of some crops.

In general, little work in food production or food security research has focused on determining whether climate trends affecting agriculture can be attributed to anthropogenic influence on the climate system. However, as the field of climate detection and attribution proceeds to finer spatial and temporal scales, and as agricultural modeling studies expand to broader scales, there should be many opportunities to link climate and crop studies in the next few years. Importantly, climate attribution is increasingly documented not only for measures of average conditions over growing seasons, but also for extremes. For instance, Min et al. (2011) attributed changes in rainfall extremes for 1951–1999 to anthropogenic activity, and these are widely acknowledged as important to cropping systems (Rosenzweig et al., 2002). Frost damage is an important constraint on crop growth in many crops, including for various high-value crops, and significant reductions in frost occurrence since 1961 have been observed and attributed to greenhouse gas (GHG) emissions in nearly every region of the world (Zwiers et al., 2011; IPCC, 2012).

Increased frequency of unusually hot nights since 1961 are also attributable to human activity in most regions (WGI AR5 Chapter 10). These events are damaging to most crops, an effect that has been observed most commonly for rice yields (Peng et al., 2004; Wassmann et al., 2009; Welch et al., 2010) as well as rice quality (Okada et al., 2011). Extremely high daytime temperatures are also damaging and occasionally lethal to crops (Porter and Gawith, 1999; Schlenker and Roberts, 2009), and trends at the global scale in annual maximum daytime temperatures since 1961 have been attributed to GHG emissions (Zwiers et al., 2011). At regional and local scales, however, trends in daytime maximum are harder to attribute to GHG emissions because of the prominent role of soil moisture and clouds in driving these trends (Christidis et al., 2005; Zwiers et al., 2011).

In addition to effects of changes in climatic conditions, there are clear effects of changes in atmospheric composition on crops. Increase of atmospheric CO_2 by greater than 100 ppm since preindustrial times has *virtually certainly* enhanced water use efficiency and yields, especially for C_3 crops such as wheat and rice, although these benefits played a minor role in driving overall yield trends (Amthor, 2001; McGrath and Lobell, 2011).

Emissions of CO_2 often are accompanied by ozone (O_3) precursors that have driven a rise in tropospheric O_3 that harms crop yields (Morgan et al., 2006; Mills et al., 2007; Section 7.3.2.1.2). Elevated O_3 since preindustrial times has *very likely* suppressed global production of major crops compared to what they would have been without O_3 increases, with estimated losses of roughly 10% for wheat and soybean and 3 to 5% for maize and rice (Van Dingenen et al., 2009). Impacts are most severe over India and China (Van Dingenen et al., 2009; Avnery et al. 2011a,b), but are also evident for soybean and maize in the USA (Fishman et al., 2010).

7.2.1.2. Fisheries Production

The global average consumption of fish and other products from fisheries and aquaculture in 2010 was 18.6 kg per person per year, derived from a total production of 148.5 million tonnes, of which 86% was used for direct human consumption. The total production arose from contributions of 77.4 and 11.2 million tonnes respectively from marine and inland capture fisheries, and 18.1 and 41.7 million tonnes respectively from marine and freshwater aquaculture (FAO, 2012). Fisheries make particular contributions to food security and more than 90% of the people engaged in the sector are employed in small-scale fisheries, many of whom are found in the poorer countries of the world (Cochrane et al., 2011). The detection and attribution of impacts are as confounded in inland and marine fisheries as in terrestrial food production systems. Overfishing, habitat modification, pollution, and interannual to decadal climate variability can all have impacts that are difficult to separate from those directly attributable to climate change.

One of the best studied areas is the Northeast Atlantic, where the temperature has increased rapidly in recent decades, associated with a poleward shift in distribution of fish (Perry et al., 2005; Brander, 2007; Cheung et al., 2010, 2013). There is *high confidence* in observations of increasing abundance of fish species in the northern extent of their ranges while decreases in abundance have occurred in the southern part (Section 30.5.1.1.1). These trends will have mixed implications for fisheries and aquaculture with some commercial species negatively and others positively affected (Cook and Heath, 2005). There is a similar well-documented example in the oceans off southeast Australia with large warming trends associated with more southward incursion of the Eastern Australian Current, resulting in southward migration of marine species into the oceans around eastern Tasmania (*robust evidence*, *high agreement*; Last et al., 2011).

As a further example, coral reef ecosystems provide food and other resources to more than 500 million people and with an annual value of US$5 billion or more (Munday et al., 2008; Hoegh-Guldberg, 2011). More than 60% of coral reefs are considered to be under immediate threat of damage from a range of local threats, of which overfishing is the most serious (Burke et al., 2011; see also Box CC-CR) and the percentage under threat rises to approximately 75% when the effect of rising ocean temperatures is added to these local impacts (Burke et al., 2011). Wilson et al. (2006) demonstrated that declines in coral reef cover typically led to declines in abundance of the majority of fish species associated with coral reefs. There is *high confidence* that the availability of fish and invertebrate species associated with coral reefs that are important in many tropical coastal fisheries is *very likely* to be reduced (Section 30.6.2.1.2). Other examples around the world are described in Section 30.5.1.1.1.

These changes are impacting marine fisheries: a recent study that examined the composition of global fisheries catches according to the inferred temperature preferences of the species caught in fisheries found that there had been changes in the species composition of marine capture fisheries catches and that these were significantly related to changes in ocean temperatures (Cheung et al. 2013; Section 6.4.1.1). These authors noted that the relative contribution to catches by warmer water species had increased at higher latitudes while the contributions of subtropical species had decreased in the tropics. These changes have negative implications for coastal fisheries in tropical developing countries, which tend to be particularly vulnerable to climate change (Cheung et al., 2013; Sections 6.4.3, 7.5.1.1.2).

There is considerably less information available on climate change impacts on fisheries and fishery resources in freshwater systems and aquaculture. Considerable attention has been given to the impacts of climate change in some African lakes but with mixed interpretations (Section 22.3.3.1.4). There is evidence that increasing temperature has reduced the primary productivity of Lake Tanganyika in East Africa and a study by O'Reilly et al. (2003) estimated that this would have led to a decrease of approximately 30% in fish yields. However, Sarvala et al. (2006) disagreed and concluded that observed decreases in the fish catches could be explained by changed fishery practices. There has been a similar difference of opinion for Lake Kariba, where Ndebele-Murisa et al. (2011) argued that a reduction in fisheries productivity had been caused by climate change while Marshall (2012) argued that the declines in fish catches can only have been caused by fishing. There is *medium confidence* that, in India, changes in a number of climate variables including an increase in air temperature, regional monsoon variation, and a regional increase in incidence of severe storms have led to changes in species composition in the River Ganga and to have reduced the availability of fish spawn for aquaculture in the river Ganga while having positive impacts on aquaculture on the plains through bringing forward and extending the breeding period of the majors carps (Vass et al., 2009).

Frequently Asked Questions

FAQ 7.1 | What factors determine food security and does low food production necessarily lead to food insecurity?

Observed data and many studies indicate that a warming climate has a negative effect on crop production and generally reduces yields of staple cereals such as wheat, rice, and maize, which, however, differ between regions and latitudes. Elevated CO_2 could benefit crops yields in the short term by increasing photosynthesis rates; however, there is big uncertainty in the magnitude of the CO_2 effect and the significance of interactions with other factors. Climate change will affect fisheries and aquaculture through gradual warming, ocean acidification, and changes in the frequency, intensity, and location of extreme events. Other aspects of the food chain are also sensitive to climate but such impacts are much less well known. Climate-related disasters are among the main drivers of food insecurity, both in the aftermath of a disaster and in the long run. Drought is a major driver of food insecurity, and contributes to a negative impact on nutrition. Floods and tropical storms also affect food security by destroying livelihood assets. The relationship between climate change and food production depends to a large degree on when and which adaptation actions are taken. Other links in the food chain from production to consumption are sensitive to climate but such impacts are much less well known.

7.2.1.3. Livestock Production

In comparison to crop and fish production, considerably less work has been published on observed impacts for other food production systems, such as livestock or aquaculture, and to our knowledge nothing has been published for hunting or collection of wild foods other than for capture fisheries. The relative lack of evidence reflects a lack of study in this topic, but not necessarily a lack of real-world impacts of observed climate trends. A study of blue-tongue virus, an important ruminant disease, evaluated the effects of past and future climate trends on transmission risk, and concluded that climate changes have facilitated the recent and rapid spread of the virus into Europe (Guis et al., 2012). Ticks that carry zoonotic diseases have also *likely* changed distribution as a consequence of past climate trends (Section 23.4.2).

7.2.2. Food Security and Food Prices

Food production is an important aspect of food security (Section 7.1), and the evidence that climate change has affected food production implies some effect on food security. Yet quantifying this effect is an extremely difficult task, requiring assumptions about the many non-climate factors that interact with climate to determine food security. There is thus limited direct evidence that unambiguously links climate change to impacts on food security.

One important aspect of food security is the prices of internationally traded food commodities (Section 7.1.3). These prices reflect the overall balance of supply and demand, and the accessibility of food for consumers integrated with regional to global markets. Although food prices gradually declined for most of the 20th century (FAO, 2009b) since AR4 there have been several periods of rapid increases in international food prices (Figure 7-3). A major factor in recent price changes has been increased crop demand, notably via increased use in biofuel production related both to energy policy mandates and oil price fluctuations (Roberts and Schlenker, 2010; Mueller et al., 2011; Wright, 2011). Yet fluctuations and trends in food production are also widely believed to have played a role in recent price changes, with recent price spikes often following climate extremes in major producers (Figure 7-3). Moreover, some of these extreme events have become more likely as a result of climate trends (Table 18-3). Domestic policy reactions can also amplify international price responses to weather events, as was the case with export bans announced by several countries since 2007 (FAO, 2008). In a study of global production responses to climate trends (Lobell et al., 2011a) estimated a price increase of 19% due to the impacts of temperature and precipitation trends on supply, or an increase of 6% once the beneficial yield effects of increased CO_2 over the study period were considered. Because the price models were developed for a period ending in 2003, these estimates do not account for the policy responses witnessed in recent years which have amplified the price responses to weather.

7.3. Assessing Impacts, Vulnerabilities, and Risks

7.3.1. Methods and Associated Uncertainties

7.3.1.1. Assessing Impacts

Methods developed or extended since AR4 have resulted in more robust statements on climate impacts, both in the literature and in Section 7.3.2. Two particular areas, which are explored below, are improved quantification and presentation of uncertainty; and greater use of historical empirical evidence of the relationship between climate and food production.

The methods used for field and controlled environment experiments remain similar to those at the time of AR4. There has been a greater use of remote sensing and geographic information systems for assessing temporal and spatial changes in land use, particularly in agricultural land use for assessment of food security status (Thenkabail et al., 2009;

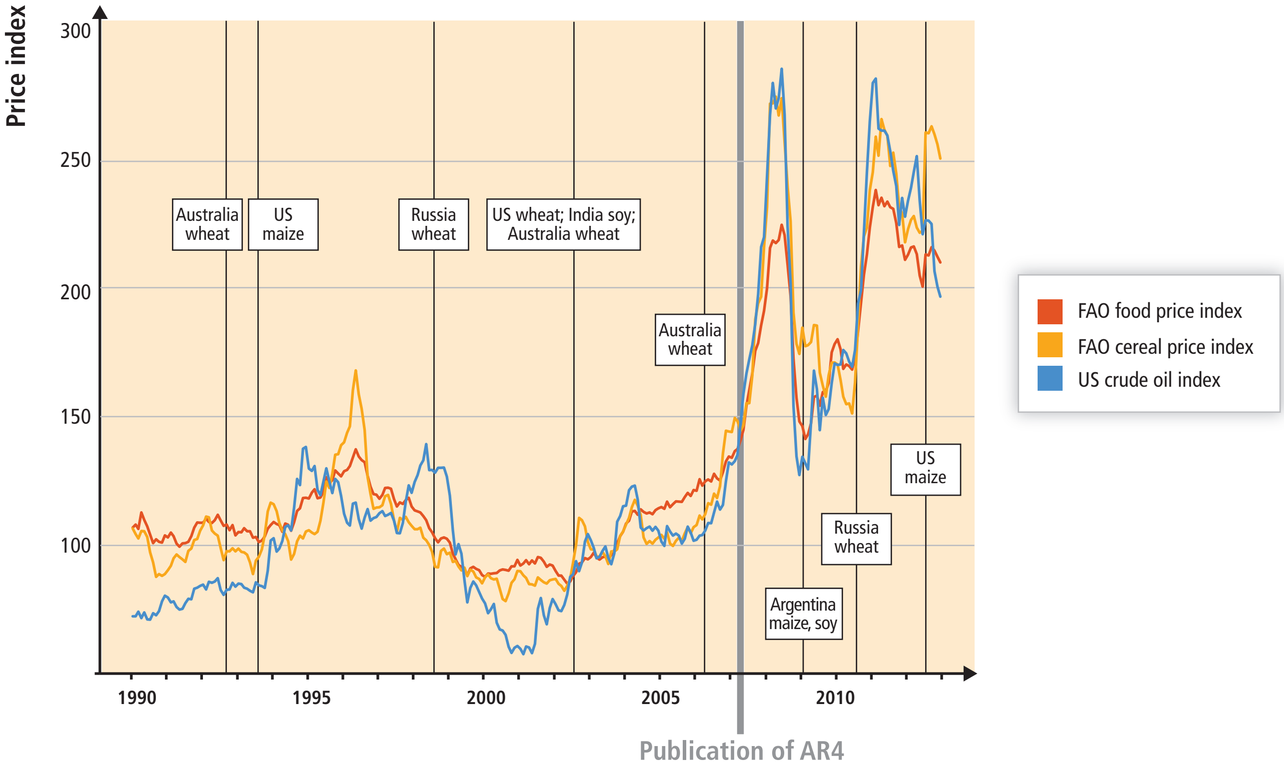


Figure 7-3 | Since the AR4, international food prices have reversed historical downward trend. The plot shows the history of FAO food and cereal price indices (composite measures of food prices), with vertical lines indicating events when a top five producer of a crop had yields 25% below trend line (indicative of a seasonal climate extreme). Australia is included despite not being a top five producer, because it is an important exporter and the drops were 40% or more below trend line. Prices may have become more sensitive to weather-related supply shortfalls in recent years. At the same time, food prices are increasingly associated with the price of crude oil (blue line), making attribution of price changes to climate difficult. Thus, there is clear evidence since AR4 that prices can rise rapidly, but the role of weather in these increases remains unclear. All indices are expressed as percentage of 2002–2004 averages. Food price and crop yield data from FAO (http://www.fao.org/worldfoodsituation/foodpricesindex and http://faostat.fao.org/) and oil price data from http://www.eia.gov.

Fishman et al., 2010; Goswami et al., 2012). There has also been an increase in the number of Free Air Concentration Enrichment (FACE) studies that examine O_3 instead of, or in addition to, CO_2. In agriculture, FACE experiments have been used for assessing impacts of atmospheric CO_2 on grain yield, quality characteristics of important crops (Erbs et al., 2010), elemental composition (Fernando et al., 2012), and diseases (Chakraborty et al., 2011; Eastburn et al., 2011). A number of meta-analyses of experimental studies, in particular FACE studies, have been made since AR4. However, debate continues on the disparities between results from FACE experiments and non-FACE experiments, such as in open-top chambers or greenhouses. As reported in AR4, FACE studies tend to show lower elevated CO_2 responses than non-FACE studies. Although some authors have claimed that the results of the two are statistically indistinct, others have argued that the results are similar only when the FACE experiments are grown under considerably more water stress than non-FACE experiments (Ainsworth et al., 2008; Kimball, 2010). Hence comparisons between different methodologies must take care to control for differences in water availability and microclimate. Another reason for differences between experiments may be differences in the temporal variance of CO_2, that is, whether concentrations are fluctuating or constant (Bunce, 2012). Unfortunately, the FACE experiments are carried out mostly in the USA and in China, and thus limited to specific environmental conditions, which do not fully reflect tropical or subtropical conditions, where CO_2 and soil nutrient interactions could lead to large differences in photosynthesis rate, water use, and yield. Also, the number of FACE studies is still quite low, which limits statistical power when evaluating the average yield effects of elevated CO_2 or interactions with temperature and moisture (Section 7.3.2).

Numerical simulation models can be used to investigate a larger number of possible environmental and management conditions than possible via physical experiments. This, in turn, enables a broader range of statements regarding the possible response of food production systems to climate variability and change. Previous assessment reports have documented new knowledge resulting from numerical simulation of the response of food production to climate change. AR4 noted the increasing number of regional studies, which is a trend that has continued to date (Craufurd et al., 2013; Zhu et al., 2013). Since AR4, crop models have been used to examine a large number of management and environmental conditions, such as interactions among various components of food production systems (Lenz-Wiedemann et al., 2010), determination of optimum crop management practices (Soltani and Hoogenboom, 2007), vulnerability and adaptability assessments (Sultana et al., 2009), evaluation of water consumption and water use efficiency (Kang et al., 2009; Mo et al., 2009), and fostering communication among scientists, managers, policymakers, and planners.

The trend toward quantification of uncertainty in both climate and its impacts has continued since AR4. Novel developments include methodologies to assess the impact of climate model error on projected agricultural output, particularly for crops (Ramirez-Villegas et al., 2013, Watson and Challinor, 2013). Models that integrate crop growth models as part of broader land surface and earth systems models (Bondeau et al., 2007; Osborne et al., 2007) are also increasingly common. Ensemble techniques for climate impacts, which were in their infancy at AR4, now include the use of Bayesian methods to constrain crop model parameters (Tao et al., 2008b, 2009a; Iizumi et al., 2009). It is also increasingly common to assess both biophysical and socioeconomic drivers of crop productivity within the same study (Fraser et al., 2008; Reidsma et al., 2009; Challinor et al., 2010; Tao et al., 2011b). Finally, an important recent development is the systematic comparison of results from different modeling and experimental approaches for providing insights into model uncertainties as well as to develop risk management (Challinor and Wheeler, 2008; Kang et al., 2009; Schlenker and Lobell, 2010; Rosenzweig et al., 2013, 2014).

Increased quantification of uncertainty can lead to clear statements regarding climate impacts. Studies with different methods have been shown to produce convergent results for some crops and locations (Challinor et al., 2009; *medium evidence*, *medium agreement*). The methods used to describe uncertainty have also improved since AR4. The projected range of global and local temperature changes can be described by quantifying uncertainty in the temporal dimension, rather than that in temperature itself (Joshi et al., 2011), and a similar approach can be used for crop yield (Figure 7-5). Descriptions of uncertainty that present key processes and trade-offs, rather than ranges of outcome variables, have also proved to be useful tools for understanding future impacts (Thornton et al., 2009a; Hawkins et al., 2012; Ruane et al., 2013). Section 7.3.2 reviews the results of such studies.

A considerable body of work since AR4 has used extensive data sets of country-, regional-, and farm-level crop yield together with observed and/or simulated weather time series to assess the sensitivity of food production to weather and climate (Tao et al., 2009a, 2011). Statistical models offer a complement to more process-based model approaches, some of which require many assumptions about soil and management practices. Process-based models, which extrapolate based on measured interactions and mechanisms, can be used to develop a causal understanding of the empirically determined relationships in statistical models (cf. Schlenker and Roberts, 2009; Lobell et al., 2013a). Although statistical models forfeit some of the process knowledge embedded in other approaches, they can often reproduce the behavior of other models (Iglesias et al., 2000; Lobell and Burke, 2010) and can leverage within one study a growing availability of crop and weather data (Welch et al., 2010; Lobell et al., 2011b). However, statistical models usually exclude the direct impact of elevated CO_2, making multi-decadal prediction problematic. In determining future trends, crop models of all types can extrapolate only based on historically determined relationships. Agro-climatic indices provide an alternative to crop models that avoid various assumptions by developing metrics, rather than providing yield predictions per se (Trnka et al., 2011). However, correlations between climate or associated indices and yield are not always statistically significant.

The robustness of crop model results depends on data quality, model skill prediction, and model complexity (Bellocchi et al., 2010). Modeling and experiments are each subject to their own uncertainties. Measurement uncertainty is a feature of field and controlled environment experiments. For example, interactions among CO_2 fertilization, temperature, soil nutrients, O_3, pests, and weeds are not well understood (Soussana et al., 2010) and therefore most crop models do not include all of these effects, or broader issues of water availability, such as competition for water between industry and households (Piao et al., 2010). There are also uncertainties associated with generalizing the results of field experiments, as each one has been conducted relatively few times under a relatively small range of environmental and management conditions, and for a limited number of genotypes. This limits breadth of applicability both through limited sample size and limited representation of the diversity of genotypic responses to environment (Craufurd et al., 2013). For example, yield increases normalized by increase in CO_2 have been found to vary between zero and more than 30% among crop varieties (Tausz et al., 2011).

Uncertainty in climate simulation is generally larger than, or sometimes comparable to, the uncertainty in crop simulation using a single crop model (Iizumi et al., 2011), although temperature-driven processes in crop models have been shown to dominate the causes of uncertainty (Koehler et al., 2013). There is significant uncertainty in agricultural simulation arising from climate model error. Since AR4 the choice of method for General Circulation Model (GCM) bias correction has been identified as a significant source of uncertainty (Hawkins et al., 2012). There is also a contribution to uncertainty in crop model output from yield measurement error, through the calibration procedure. Yield measurements rarely have associated error bars to give an indication of accuracy. Greater access to accurate regional-scale crop yield data can lead to decreased uncertainty in projected yields (Watson and Challinor, 2013).

The use of multiple crop models in impacts studies is relatively rare. Field-scale historical model intercomparisons have shown variations in the simulation of mean yield and above-ground biomass of more than 60% (Palosuo et al., 2011). Early results from impacts studies with multiple crop models suggest that the crop model uncertainty can be larger than that caused by GCMs, due in particular to high temperature and temperature-by-CO_2 interactions (Asseng et al., 2013). However, in contrast to absolute values, yield changes can be consistent across crop models (Olesen et al., 2007). Given these different strengths and weaknesses, and associated dependencies, it is critical that both experimental and modeling lines of evidence, and their uncertainties, are examined carefully when drawing conclusions regarding impacts, vulnerabilities, and risks. This approach to assessment is applied to each of the topics described in the rest of the chapter.

The methods used for assessing impacts, vulnerabilities, and risks in fisheries and aquaculture face the constraint that meaningful controlled experiments are usually not practical for fisheries in large rivers, lakes, and marine environments because of the typical open and connected nature of these ecosystems. Experimentation has been used to examine responses to impacts at the scale of individual species, for example, to demonstrate the impacts of high atmospheric CO_2 in reducing coral calcification and growth (Hoegh-Guldberg et al., 2007) and to study the temperature tolerances of different cultured species (Ficke et al., 2007; De Silva and Soto, 2009). The far more common approach, however, is the empirical analysis of data collected in the field. This has been used to examine the effect of climate-related factors on recruitment to a population, growth, and population production of specific species, for example (Brander, 2010; see also Chapters 6 and 30). Different modeling approaches have also been used to integrate available information and assess the impacts of climate change on ecosystems and fish production at scales from national to global (Cheung et al., 2010; Fulton, 2011; Merino et al., 2012; see also Section 6.5). Efforts to assess the vulnerability of those dependent on fisheries and aquaculture have increased in recent years and range from studies that use available information on exposure, sensitivity, and adaptive capacity to provide an index of vulnerability (Allison et al., 2009; Cinner at al., 2012) to more detailed social and economic studies focused on particular communities or localities (Daw et al., 2009).

7.3.1.2. Treatment of Adaptation in Impacts Studies

Adaptation occurs on a range of time scales and by a range of actors. Incremental adaptation, such as a change in crop management, can occur relatively autonomously within farming systems. It is the type of adaptation most commonly assessed in the impacts literature, and it is the only form of adaptation discussed in Sections 7.3 and 7.4. Systemic and transformational adaptations are discussed in Section 7.5. Methods exist to examine impacts and adaptation together in the context of non-climatic drivers (Mandryk et al., 2012), but conclusions are difficult to generalize.

7.3.2. Sensitivity of Food Production to Weather and Climate

7.3.2.1. Cereals and Oilseeds

7.3.2.1.1. Mean and extremes of temperature and precipitation

Both statistical and process-based models have been used widely since AR4 to assess the response of crop yield to temperature. Model results confirm the importance of known key physiological processes, such as the shortening of the time to maturity of a crop with increasing mean temperature (Iqbal et al., 2009), decline in grain set when high temperatures occur during flowering (Moriondo et al., 2011), and increased water stress at high temperatures throughout the growing cycle (Lobell et al., 2013a). Temperature responses are generally well understood for temperatures up to the optimum temperature for crop development. The impacts of prolonged periods of temperatures beyond the optimum for development are not as well understood (Craufurd and Wheeler, 2009). For example, temperatures above 32-34°C after flowering appear to speed senescence rapidly in wheat (Asseng et al., 2011; Lobell et al., 2012), but many crop models do not represent this process (Sanchez et al., 2014). Crop models can be used to quantify abiotic stresses such as these, although only by hypothesizing that the functional responses to weather derived from experiments are valid at regional scales. Thus, although many fundamental biophysical processes are understood at the plant or field scale, it remains difficult to quantify the extent to which these mechanisms are responsible for the observed regional-scale relationships between crop yield and weather. Despite these particular areas where specific understanding is lacking, the evidence from regional-scale statistical analyses (Schlenker and Roberts, 2009) and process-based models shows clear negative impacts of temperatures above 30°C to 34°C on crop yields (depending on the crop and region) (*high evidence*, *high agreement*).

The overall relationship between weather and yields is often crop and region specific, depending on differences in baseline climate, management and soil, and the duration and timing of crop exposure to various conditions. For example, rice yields in China have been found to be positively correlated with temperature in some regions and negatively correlated in others (Zhang et al., 2008, 2010). The trade-offs that occur in determining yield are therefore region-specific. This difference may be due to positive correlation between temperature and solar radiation in the former case, and negative correlation between temperature and water stress in the latter case. Similarly, although studies consistently show spikelet sterility in rice for daytime temperatures exceeding 33°C (Jadadish et al., 2007; Wassmann et al., 2009), some statistical studies find a positive effect of daytime warming on yields because these extremes are not reached frequently enough to affect yields (Welch et al., 2010). Responses to temperature may vary according whether yields are limited by low or high temperatures. However, there is evidence that high temperatures will limit future yields even in cool environments (Semenov et al., 2012; Teixeira et al., 2013).

The relative importance of temperature and water stress for crop productivity can be assessed using models, and can vary according to the criteria used for assessment (Challinor et al., 2010). There are also some cases where the sign of a correlation depends on the direction of the change. For example, Thornton et al. (2009b) found that the response of crop yields to climate change in the drylands of East Africa is insensitive to increases in rainfall, as wetter climates are associated with warmer temperatures that act to reduce yields. Because precipitation exhibits more spatial variability than temperature, temporal variations in the spatial average of precipitation tend to diminish as the spatial domain widens. As a result, precipitation becomes less important as a predictor of crop yields at broad scales (Lobell and Field, 2007; Li et al., 2010). Similarly, projected changes in precipitation from climate models tend to be more spatially variable than temperature, leading to the greater importance of projected temperatures as the spatial scale of analysis grows wider (Lobell and Burke, 2008). There is also evidence that where irrigation increases over time the influence of temperature on yields starts to dominate over that of precipitation (Hawkins et al., 2012). The impact of drought on crop yield is a more common topic of research than the impact of floods.

Analysis of 66 yield impact studies for major cereals, including both pre- and post-AR4 contributions, gives broadly similar results to AR4 (Figure 7-4). Figure 7-4 shows that yields of maize and wheat begin to decline with 1°C to 2°C of local warming in the tropics. Temperate maize and tropical rice yields are less clearly affected at these temperatures, but significantly affected with warming of 3°C to 5°C. These data confirm AR4 findings that even slight warming will decrease yields in low-latitude regions (medium evidence, high agreement). However, although AR4 had few indications of yield reductions at less than 2°C of local warming, the new analysis has, in the absence of incremental adaptation, more yield decreases than increases at all temperatures. Hence, although AR4 concluded with *medium confidence* that in mid- to high-latitude

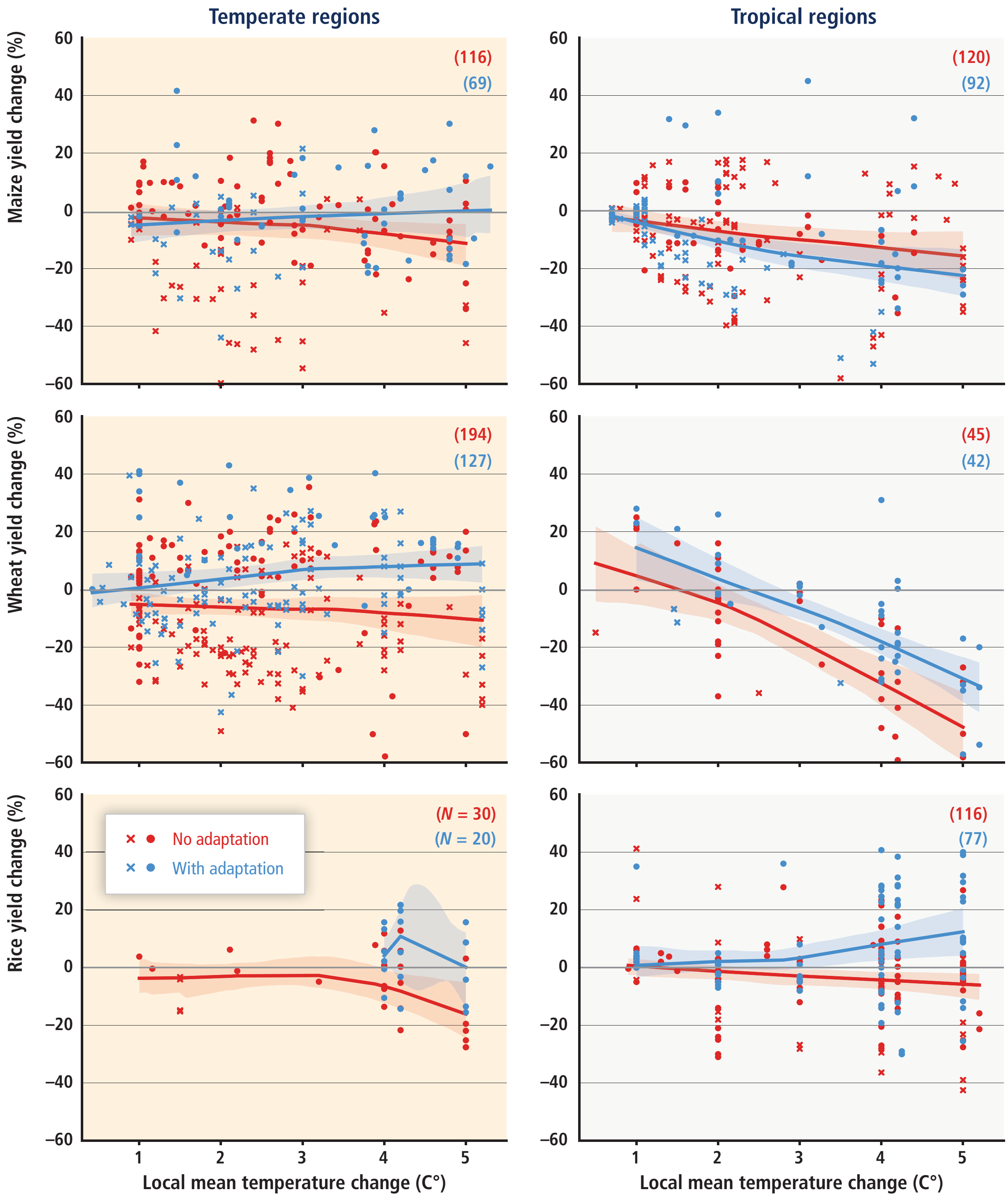


Figure 7-4 | Percentage simulated yield change as a function of local temperature change for the three major crops and for temperate and tropical regions. Dots indicate where a known change in atmospheric CO_2 was used in the study; remaining data are indicated by x. Note that differences in yield value between these symbols do not measure the CO_2 fertilization effect, as changes in other factors such as precipitation may be different between studies. Non-parametric regressions (LOESS, span = 1 and degree = 1) of subsets of these data were made 500 times. These bootstrap samples are indicated by shaded bands at the 95% confidence interval. Regressions are separated according to the presence (blue) or absence (red) of simple agronomic adaptation (Table 7-2). In the case of tropical maize, the central regression for absence of adaptation is slightly higher than that with adaptation. This is due to asymmetry in the data—not all studies compare adaptated and non-adapted crops. Figure 7-8 presents a pairwise adaptation comparison. Note that four of the 1048 data points across all six panels are outside the yield change range shown. These were omitted for clarity. Some of the studies have associated temporal baselines, with center points typically between 1970 and 2005. Note that local warming in cropping regions generally exceeds global mean warming (Figure 21-4). Data are taken from a review of literature: Rosenzweig and Parry, 1994; Karim et al., 1996; El-Shaher et al., 1997; Kapetanaki and Rosenzweig, 1997; Lal et al., 1998; Moya et al., 1998; Winters et al., 1998; Yates and Strzepek, 1998; Alexandrov, 1999; Kaiser, 1999; Reyenga et al., 1999; Alexandrov and Hoogenboom, 2000; Southworth et al., 2000; Tubiello et al., 2000; DeJong et al., 2001; Izaurralde et al., 2001; Aggarwal and Mall, 2002; Abou-Hadid, 2006; Alexandrov et al., 2002; Corobov, 2002; Chipanshi et al., 2003; Easterling et al., 2003; Jones and Thornton, 2003; Luo et al., 2003; Matthews and Wassmann, 2003; Droogers, 2004; Howden and Jones, 2004; Butt et al., 2005; Erda et al., 2005; Ewert et al., 2005; Gbetibouo and Hassan, 2005; Izaurralde et al., 2005; Porter and Semenov, 2005; Sands and Edmonds, 2005; Thomson et al., 2005; Xiao et al., 2005; Zhang and Liu, 2005; Zhao et al., 2005; Abraha and Savage, 2006; Brassard and Singh, 2007, 2008; Krishnan et al., 2007; Lobell and Ortiz-Monasterio, 2007; Xiong et al., 2007; Tingem et al., 2008; Walker and Schulze, 2008; El Maayar et al., 2009; Schlenker and Roberts, 2009; Thornton et al., 2009a, 2010, 2011; Tingem and Rivington, 2009; Byjesh et al., 2010; Chhetri et al., 2010; Liu et al., 2010; Piao et al., 2010; Tan et al., 2010; Tao and Zhang, 2010, 2011a,b; Arndt et al., 2011; Deryng et al., 2011; Iqbal et al., 2011; Lal, 2011; Li et al., 2011; Rowhanji et al., 2011; Shuang-He et al., 2011; Osborne et al., 2013.

regions moderate warming will raise crop yields, new knowledge suggests that temperate wheat yield decreases are *about as likely as not* for moderate warming. A recent global crop model intercomparison for rice, wheat, and maize shows similar results to those presented here, although with less impacts on temperate rice yields (Rosenzweig et al., 2013, 2014). That study also showed that crop models without explicit nitrogen stress fail to capture the expected response.

Quantitative assessments of yield changes can be found in Section 7.4. Across the globe, regional variability, which has not been summarized in meta-analyses except in contributing to the spread of data (Figure 7-4), will be important in determining how climate change affects particular agricultural systems.

7.3.2.1.2. Impact of carbon dioxide and ozone

There is further observational evidence since AR4 that response to a change in CO_2 depends on plant type: C_3 or C_4 (DaMatta et al., 2010). The effect of increase in CO_2 concentration tends to be higher in C_3 plants (wheat, rice, cotton, soybean, sugar beets, and potatoes) than in C_4 plants (corn, sorghum, sugarcane), because photosynthesis rates in C_4 crops are less responsive to increases in ambient CO_2 (Leakey, 2009). The highest fertilization responses have been observed in tuber crops, which have large capacity to store extra carbohydrates in belowground organs (Fleisher et al., 2008; Högy and Fangmeier, 2009). There is observational evidence, new since AR4, that the response of crops to CO_2 is genotype specific (Ziska et al., 2012). For example, yield enhancement at 200 ppm additional CO_2 ranged from 3 to 36% among rice cultivars (Hasegawa et al., 2013).

FACE studies have shown that the impact of elevated CO_2 varies according to temperature and availability of water and nutrients, although the strong geographical bias of FACE studies toward temperate zones limits the strength of this evidence. FACE studies have shown that yield enhancement by elevated CO_2 is limited under both low (Shimono et al., 2008; Hasegawa et al., 2013) and high temperature. Theory suggests that water-stressed crops will respond more strongly to elevated CO_2 than well-watered crops, because of CO_2-induced increases in stomatal resistance. This suggests that rain-fed cropping systems will benefit more from elevated CO_2 than irrigated systems.

Both the Third Assessment Report (TAR) and AR4 cited the expectation that rain-fed systems benefit more from elevated CO_2 than systems under wetter conditions. New evidence based on historical observations supports this notion by demonstrating that the rate of yield gains in rain-fed systems is higher in dry years than in wet years (McGrath and Lobell, 2011). However, this response is not seen consistently across models and FACE meta-analyses, and there is some suggestion that the relationship between water stress and assimilation may vary with spatial scale, with canopy analyses showing a reversal of the expected leaf-level dry versus wet signal (Challinor and Wheeler, 2008).

O_3 in the stratosphere provides protection from lethal short-wave solar ultraviolet radiation, but in the troposphere it is a phytotoxic air pollutant. The global background concentration of O_3 has increased since the preindustrial era due to anthropogenic emission of its precursors (carbon monoxide, volatile organic compounds, and oxides of nitrogen), by vehicles, power plants, biomass burning, and other sources of combustion. Like CO_2, O_3 is taken up by green leaves through stomata during photosynthesis but, unlike CO_2, its concentration is significantly variable depending on geographic location, elevation, and extent of anthropogenic sources. Being a powerful oxidant, O_3 and its secondary by-products damage vegetation by reducing photosynthesis and other important physiological functions (Mills et al., 2009; Ainsworth and McGrath, 2010). This results in stunted crop plants, inferior crop quality, and decreased yields (Booker et al., 2009; Fuhrer, 2009; Vandermeiren et al., 2009; Pleijel and Uddling, 2012) and poses a growing threat to global food security (*robust evidence*, *high agreement*).

The literature published since AR4 further corroborates the negative impacts of increasing concentrations of surface O_3 on yield at global (Van Dingenen et al., 2009; Avnery et al., 2011a,b; Teixeira et al., 2011) and regional scales (Northern Hemisphere: Hollaway et al., 2011; USA: Emberson et al., 2009; Fuhrer, 2009; Fishman et al., 2010; India: Roy et al., 2009; Rai et al., 2010; Sarkar and Agrawal, 2010; China: Wang et al., 2007, 2011; Piao et al., 2010; Bangladesh: Akhtar et al., 2010; Europe: Hayes et al., 2007; Fuhrer, 2009; Vandermeiren et al., 2009). Global estimates of yield losses due to increased O_3 in soybean, wheat, and maize in 2000 ranged from 8.5 to 14%, 3.9 to 15%, and 2.2 to 5.5% respectively, amounting to economic losses of US$11 to 18 billion (Avnery et al., 2011a). O_3 may have a direct effect on reproductive process, leading to reduced seed and fruit development and abortion of developing fruit (*robust evidence*, *high agreement*; Royal Society, 2008).

The interactive effects of O_3 with other environmental factors such as CO_2, temperature, moisture, and light, are important but not well understood. Generally, the ambient and increasing concentrations of O_3 and CO_2 individually exert counteractive effects on C_3 plants (Tianhong et al., 2005; Ainsworth et al., 2008; Gillespie et al., 2012), but their interactive effect may compensate for each other (Ainsworth et al., 2008; Taub et al., 2008; Gillespie et al., 2012). However, the losses might be greater when elevated O_3 combines with high temperature (Long, 2012) particularly during grain filling of wheat, when elevated O_3 causes premature leaf senescence (Feng et al., 2008b, 2011). Periods of abundant radiation and adequate water supply are favorable for both agricultural production and the formation of surface O_3; thus, the effects of O_3 on crops can be difficult to detect (Long, 2012).

7.3.2.2. Other Crops

Earlier flowering and maturity have been observed (*robust evidence*, *high agreement*) worldwide in grapes (Duchêne et al., 2010; García-Mozo et al., 2010; Jorquera-Fontena and Orrego-Verdugo, 2010; Sadras and Petrie, 2011; Webb et al., 2011), apples (Fujisawa and Koyabashi, 2010; Grab and Craparo, 2011), and other perennial horticultural crops (Glenn et al., 2013). Cassava (also known as manioc) is an important source of food for many people in Africa and Latin America and recent studies suggest (*medium evidence*, *medium agreement*) that future climate should benefit its productivity as this crop is characterized by elevated optimum temperature for photosynthesis and growth, and a positive response to CO_2 increases (El-Sharkawy, 2012; Jarvis et al., 2012; Rosenthal and Ort, 2012).

7.3.2.3. Pests, Weeds, Diseases

As a worldwide average, yield loss in major crop species due to animal pests and (non-virus) pathogens, in the absence of any physical, biological, or chemical crop protection, has been estimated at 18% and 16%, respectively (Oerke, 2006), but weeds produce the highest potential loss (34%). Climate change will alter potential losses to many pests and diseases. Changes in temperature can result in geographic shifts through changes in seasonal extremes, and thus, for example, overwintering and summer survival. CO_2 and O_3 can either increase or decrease plant disease, and can exhibit important interactions (Chakraborty and Newton, 2011; Garrett et al., 2011), suggesting the need for system-specific risk assessment (Chakraborty et al., 2008; Eastburn et al., 2011). Interactions with landscape effects may be particularly important in forests and grasslands (Pautasso et al., 2010).

The rarity of long-term studies of plant diseases and pests is a problem for the evaluation of climate change effects, but there are some examples of the potential for such analyses. Ongoing wheat experiments at Rothamsted Research Station UK, maintained for more than 160 years, have revealed shifts in foliar wheat pathogens linked to rainfall, temperature, and sulfur dioxide (SO_2) emissions (Bearchell et al., 2005; Shaw et al., 2008). Wheat rust risk has been observed to respond to El Niño-Southern Oscillation (ENSO; Scherm and Yang, 1995). Over almost 7 decades, earlier and more frequent epidemics of potato late blight, and more frequent pesticide use, were observed in Finland, associated with changing climate conditions and lack of crop rotation (Hannukkala et al., 2007).

Changes in climate are expected to affect the geographic range of specific species of insects and diseases for a given crop growing region. For example, Cannon (1998) has suggested that migratory insects could colonize crops over a larger range in response to temperature increases, with subsequent reductions in yield. Climate change may also be a factor in extending the northward migration of agronomic and invasive weeds in North America (Ziska et al., 2011). Weed species also possess characteristics that are associated with long-distance seed dispersal, and it has been suggested (Hellman et al., 2008) that they may migrate rapidly with increasing surface temperatures. Predator and insect herbivores respond differently to increasing temperature, leading to possible reductions in insect predation and thus greater insect numbers. However, ecosystems are complex and insect and disease occurrence can go down as well as up. Overall, our ability to predict CO_2/climate change impacts on pathogen biology and subsequent changes on yield is limited because, with few exceptions (Savary et al., 2011), experimental data are not available and analyses focus on individual diseases rather than the complete set of important diseases (*medium evidence*, *medium agreement*).

Elevated CO_2 can reduce yield losses due to weeds for C_3 crops (soybean, wheat, and rice), as many agricultural weeds are C_4 species; and the C_3 pathway, in general, shows a stronger response to rising CO_2 levels. However, both C_3 and C_4 weed species occur in agriculture, and there is a wide range of responses among these species to recent and projected CO_2 levels (Ziska, 2010). For example, in the USA, every crop, on average, competes with an assemblage of 8 to 10 weed species (Bridges, 1992). CO_2 and climate can also affect weed demographics. For example, with field grown soybean, elevated CO_2 per se appeared to be a factor in increasing the relative proportion of C_3 to C_4 weedy species with subsequent reductions in soybean yields (Ziska and Goins, 2006). For rice and barnyard grass (C_4), increasing CO_2 favored rice, but if both temperature and CO_2 increased simultaneously, the C_4 weed was favored, primarily because higher temperatures resulted in increased seed yield loss for rice. For weeds that share physiological, morphological, or phenological traits with the crop, including those weeds that are wild relatives of the domesticated crop species (often among the "worst" weeds in agronomic situations, e.g., rice and red rice), the decrease in seed yield from weeds may be greater under elevated CO_2 (Ziska, 2010).

With respect to control, a number of studies have, to date, indicated a decline in herbicide efficacy in response to elevated CO_2 and/or temperature for some weed species, both C_3 and C_4 (Archambault, 2007; Manea et al., 2011). Some of the mechanisms for this are understood, for example, for the invasive plant species Canada thistle (*Cirsium arvense*), elevated CO_2 results in a greater root biomass, thus diluting the active ingredient of the herbicide used and reducing chemical control (Ziska, 2010). To date, studies on physical, cultural, or biological weed control are lacking.

7.3.2.4. Fisheries and Aquaculture

The natural and human processes in fisheries and aquaculture differ from mainstream agriculture and are particularly vulnerable to impacts and interactions related to climate change. Capture fisheries in particular, comprising the largest remaining example of harvesting natural, wild resources, are strongly influenced by global ecosystem processes. The social, economic, and nutritional requirements of the growing human population are already driving heavy exploitation of capture fisheries and rapid development of aquaculture (Section 6.4.1.1). This trend will continue over the next 20 to 30 years at least: Merino et al. (2012) forecast that in addition to a predicted small increase in marine fisheries production, between 71 and 117 million tonnes of fish will need to be produced by aquaculture to maintain current average per capita consumption of fish. The impacts of climate change add to and compound these threats to the sustainability of capture fisheries and aquaculture development (FAO, 2009a). Expected changes in the intensity, frequency, and seasonality of climate patterns and extreme events, sea level rise, glacier melting, ocean acidification, and changes in precipitation with associated changes in groundwater and river flows are expected to result in significant changes across a wide range of aquatic ecosystem types and regions with consequences for fisheries and aquaculture in many places (FAO, 2009a; see also Section 30.5.1.1). Ocean acidification will also have negative impacts on the culture of calcifying organisms (Section 30.6.2.1.4), including mollusc species of which 14.2 million tonnes were produced by aquaculture in 2010, equivalent to 23.6% of global aquaculture production (FAO, 2012). There are also concerns that climate change could lead to the spread of pathogens with impacts on wild and cultured aquatic resources (De Silva and Soto, 2009).

Given the proximity of fishing and aquaculture sites to oceans, seas, and riparian environments, extreme events can be expected to have impacts on fisheries and aquaculture with those located in low-lying areas at particular risk. The consequences of sea level rise and the expected increased frequency and intensity of storms include increased risks of loss of homes and infrastructure, increased safety risks while fishing, and the loss of days at sea because of bad weather (Daw et al., 2009). In areas that experience water stress and competition for water resources, aquaculture operations and inland fisheries production will be at risk.

Food production from fisheries and aquaculture will be affected by the sensitivity of the caught and cultured species to climate change and both positive and negative outcomes can be expected. Changes in marine and freshwater mean temperatures, ocean acidification, hypoxia, and other climate-related changes will influence the distribution and productivity of fished and farmed aquatic species (Sections 6.4.3, 7.2.1.2, 30.6.2). Changes in temperature extremes are also likely to have impacts. Many aquatic species are routinely subjected to large daily and seasonal fluctuations in temperature and are able to cope with them: for example, temperatures in shallow coastal habitats in the tropical Pacific can vary by more than 14°C diurnally (Pratchett et al., 2011). Nevertheless, distribution and productivity of aquatic species and communities are sensitive to changes in temperature extremes. A study on salmon populations in Washington State, USA (Mantua et al., 2010), demonstrated important impacts of seasonal variations and extremes. The study concluded that warming in winter and spring would have some positive impacts while increased summertime stream temperatures, seasonal low flows, and changes in the peak and base flows would have negative impacts on the populations. Coral reefs are particularly susceptible to extremes in temperature: temperatures 1°C or 2°C in excess of normal maximums for 3 to 4 weeks are sufficient to disrupt the essential relationship between endosymbiotic dinoflagellates and their coral hosts, leading to coral bleaching. Large-scale bleaching of coral reefs has increased in recent decades both in intensity and frequency (Hoegh-Guldberg et al., 2007).

The impacts of climate change on the fisheries and aquaculture sector will have implications for the four dimensions of food security, that is, availability of aquatic foods, stability of supply, access to aquatic foods, and utilization of aquatic products (FAO, 2009a). Where climate-driven ecological changes are significant, countries and communities will need to adapt through, for example, changes in fishing and aquaculture practices and operations (Section 7.5.1.1.2).

7.3.2.5. Food and Fodder Quality and Human Health

Food quality is any characteristic other than yield that is valuable to the producer or consumer. Examples include wheat protein and starch concentrations, which affect dough quality; amylose content in rice, which affects taste; and mineral concentrations, which affects nutrient intake of consumers. Climate change will have some adverse impacts on food quality through both biotic and abiotic stresses (Ceccarelli et al., 2010). These changes may affect crop quality by altering carbon and nutrient uptake and biochemical processes that produce secondary compounds or redistribute and store compounds during grain development and maturation. This in turn could impact human and livestock health by altering nutritional intake and/or affect economic value by altering traits valuable to processers or the consumers.

Change in nitrogen concentration, a proxy for protein concentration, is the most examined quality trait and since AR4 studies have been extended to almost all the major food crops. Cereals grown in elevated CO_2 show a decrease in protein (Pikki et al., 2007; Högy et al., 2009; Erbs et al., 2010; Ainsworth and McGrath, 2010; DaMatta et al., 2010; Fernando et al., 2012). Meta-analysis of 228 experimental observations finds decreases between 10 and 14% in edible portions of wheat, rice, barley, and potato, but only 1.5% in soybeans, a nitrogen-fixing legume, when grown in elevated CO_2 (Taub et al., 2008).

Mineral concentration of edible plant tissues are affected by growth in elevated CO_2 in a similar manner to nitrogen. Although there are numerous studies measuring mineral concentration, there are relatively few measurements for any given mineral relevant to human health. Although there were several studies published before the release of AR4, this topic was not covered in any depth in AR4. Meta-analysis of studies prior to 2002 finds that phosphorus, calcium, sulfur, magnesium, iron, zinc, manganese, and copper decline by 2.5 to 20% in wheat grain and leaves of numerous species in elevated CO_2, but potassium increases insignificantly in wheat grain (Loladze, 2002; Högy et al., 2009; Fernando et al., 2012). Since 2002, studies generally find decreases in zinc, sulfur, phosphorus, magnesium, and iron in wheat and barley grain; increase in copper, molybdenum, and lead (from a limited number of studies); and mixed results for calcium and potassium (Högy et al., 2009; Erbs et al., 2010; Fernando et al., 2012). Changes in mineral concentration due to elevated CO_2 are determined by several factors including crop species, soil type, tissue (tubers, leaves, or grain) and water status.

Elevated CO_2 can lower the nutritional quality of flour produced from grain cereals (Högy et al., 2009; Erbs et al., 2010) and of cassava (Gleadow et al., 2009). When coupled with increased crop and pathogen biomass, elevated CO_2 can result in increased severity of the *Fusarium pseudograminearum* pathogen, leading to shriveled grains with low market value (Melloy et al., 2010).

Extreme temperatures and elevated CO_2 concentrations reduce milling quality of rice by increasing chalkiness, but can improve taste, through, for example, reduced amylase concentration (Yang et al., 2007). Cultivars vary in their susceptibility to these processes (Ambardekar et al., 2011; Lanning et al., 2011). Overall, there is *robust evidence* and *high agreement* that elevated CO_2 on its own likely results in decreased nitrogen concentrations. Combining knowledge of nitrogen and mineral studies, there is *medium evidence* and *medium agreement* that mineral concentrations will decline. The majority of these data are from wheat, with comparatively little information from key crops such as maize, rice, potato, and cassava; thus magnitudes are uncertain for these species.

Elevated O_3 concentrations appear to have the opposite effect as elevated CO_2. Meta-analysis of about 50 wheat experiments found that elevated O_3 increased grain protein concentration by decreasing yield (Pleijel and Uddling, 2012). For other species, studies find both increases and decreases of N and several minerals (Taub et al., 2008), and as such no firm conclusions can be drawn, but they mostly respond similarly. Likewise, experiments examining the effect of drought on mineral concentrations find both decreases and increases (Ghorbanian et al., 2011; Sun et al., 2011).

Confidence in the impact of climate, CO_2, and O_3 on food quality does not imply confidence in changes regarding human health for several reasons. Processing of food affects nutrient concentrations, when the nutrient-rich outer layers of rice are removed, leaving the starch dense endosperm. Also, elevated CO_2 can increase crop yield, thus increasing the overall yield of minerals (Duval et al., 2011) and permitting greater mineral consumption. Furthermore, since calorie intake is the primary concern in many food-insecure populations, even if intake of minerals is decreased, those negative effects could be outweighed by increased calorie intake. In assessing impacts on health, current diets must be considered. Decreased mineral intake will matter for those who currently do not meet, or just barely meet, requirements, but will not affect those who already exceed requirements. Little is known about combined effects of climate change factors on food quality or the economic and behavioral changes that will occur. Thus, there is little confidence regarding effects of climate change on human health through changes in nutrient composition.

7.3.2.6. Pastures and Livestock

Pastures response to climate change is complex because, in addition to the direct major atmospheric and climatic drivers (CO_2 concentration, temperature, and precipitation), there are important indirect interactions such as plant competition, perennial growth habits, seasonal productivity, and plant-animal interactions. Projected increases in temperature and the lengthening of the growing season should extend forage production into late fall and early spring, thereby decreasing the need for accumulation of forage reserves during the winter season in USA (Izaurralde et al., 2011). In addition, water availability may play a major role in the response of pasturelands to climate change although there are differences in species response (Izaurralde et al., 2011). There is general consensus that increases in CO_2 will benefit C_3 species; however, warmer temperatures and drier conditions will tend to favor C_4 species (Hatfield et al., 2011; Izaurralde et al., 2011; Chapter 4). While elevated atmospheric CO_2 concentrations reduce sensitivity to lower precipitation in grassland ecosystems and can reduce mortality and increase recovery during severe water stress events, it is still unclear how general this result is (Soussana et al., 2010).

Temperature is an important limiting factor for livestock. As productivity increases, be it increasing milk yield in dairy cattle or higher growth rates and leanness in pigs or poultry, so metabolic heat production increases and the capacity to tolerate elevated temperatures decreases (Zumbach et al., 2008; Dikmen and Hansen, 2009). Over the long term, single-trait selection for productivity will tend to result in animals with lower heat tolerance (Hoffmann, 2010). Recent work adds to previous understanding (WGII AR4 Chapter 5) and indicates that heat stress (*medium evidence*, *high agreement*) in dairy cows can be responsible for the increase in mortality and economic losses (Vitali et al., 2009); it affects a wide range of parameters in broilers (Feng et al., 2008a); it impairs embryonic development and reproductive efficiency in pigs (Barati et al., 2008); and affects ovarian follicle development and ovulation in horses (Mortensen et al., 2009). Water stress also limits livestock systems. Climate change will affect the water resources available for livestock via impacts on runoff and groundwater (Chapter 3). Populated river basins may experience changes in river discharge, and large human and livestock populations may experience water stress such that proactive or reactive management interventions will almost certainly be required (Palmer et al., 2008). Problems of water supply for increasing livestock populations will be exacerbated by climate change in many places in sub-Saharan Africa and South Asia.

7.3.3. Sensitivity of Food Security to Weather and Climate

7.3.3.1. Non-Production Food Security Elements

As indicated in the discussion in Section 7.1.1 and Figure 7-1, food security is dependent on access and consumption patterns, food utilization and nutrition, and overall stability of the system as much as food production and availability. The overall impact of climate change on food security is considerably more complex and potentially greater than projected impacts on agricultural productivity alone. Figure 7-1 indicates the main components of food security and their key elements. All of these will be affected by climate change to some extent. For example, climate change effects on water, sanitation, and energy availability have major implications for food access and utilization as well as availability. Likewise, changes in the frequency and severity of climate extremes can affect stability of food availability and prices, with consequent impacts on access to food.

7.3.3.2. Accessibility, Utilization, and Stability

7.3.3.2.1. Climate change impacts on access

As noted in the discussion in Section 7.1.3, change in the levels and volatility of food prices is a key determinant of food access. Given the hypothesis that climate change will be a contributing factor to food price increases, and hence its affordability, the vulnerability of households to reduced food access depends on their channel of food access (*medium evidence*, *medium agreement*). Table 7-1 divides households into five main categories of food access, indicating their relative impacts of food price increases.

Concern about the impact of increased food prices on poverty and food security arises due to the high share of income that poor consumers spend on food, thus generating a disproportionately negative effect of price increases on this group (FAO, 2011). A study by the World Bank estimated a net increase of 44 million people in extreme poverty in low- and middle-income countries as a result of food price increases since June 2010 (Ivanic et al., 2011).

The distribution of net food buyers and net food sellers varies considerably across countries and can be expected to change with the process of economic development (Zezza et al., 2008; Aksoy et al., 2010; FAO, 2011). Changing consumption patterns associated with dietary transitions that accompany income growth, urbanization, market development, and trade liberalization determine the rate and nature of food demand growth and nutritional levels, and thus is a key determinant of global and local food security (Kearney, 2010). However, the evidence base on potential climate change impacts on consumption patterns, or on other non-production elements of food security is thin, particularly when

Table 7-1 | Households divided into five categories of food access, indicating the impacts of food price increases.

Food access category	Characteristics	Impacts of food price increase on food access
Primarily subsistence (autarkic)	Subsistence farmers, herders, fishers, and forest-dependent populations; generally low share of population (Karfakis et al., 2011)	Limited impact
Food producers: net sellers	Generally lower share of population compared with net buyers (Aksoy and Sid-Dimelik, 2008; Zezza et al., 2008; FAO, 2011)	Positive impact through increased income effect. Major beneficiaries are those with greatest surplus (e.g., larger, more commercialized farms) (FAO, 2011)
Food producers: net buyers	Majority of poor rural households (IFAD, 2010; FAO, 2011)	Ambiguous: depends on relative size of income and price effects, but generally expected to be negative due to high share of income spent on food (Ivanic and Martin, 2008; FAO, 2011; Ivanic et al., 2011)
Rural non-farming households	Rural landless: characterized by high rates of food insecurity; average share of population for 15 low-income countries was 22% (Aksoy et al., 2010)	Negative impact due to high share of income spent on food; however, some limited evidence that wage increases may accompany price increases, in which case overall effects are ambiguous (Aksoy and Sid-Dikmelik, 2008; FAO, 2011)
Urban consumers	Growing share of population in most countries (IFAD, 2010)	Negative impact by reducing food affordability. Especially vulnerable to changes in global food prices, as they are more likely to consume staple foods derived from tradable commodities (FAO, 2008; Ivanic et al., 2011)

compared with the literature on climate change impacts on food production and availability.

Current and future variation in the distribution and vulnerability to loss of food access across household types makes impacts assessment complex and difficult. Nonetheless, there are reasons for concern about food access due to the current high rates of food insecurity in many low income countries. Agricultural producers who are net food buyers are particularly vulnerable. Similarly, low-income agricultural dependent economies that are net food importers, which are those that already have high rates of food insecurity, could experience significant losses in food access through a double negative effect on reduced domestic agricultural production and increased food prices on global markets.

7.3.3.2.2. Climate change impacts on stability

There is increasing evidence of and confidence in the effect of climate change on increasing the incidence and frequency of some types of climate extreme events (IPCC, 2012), and this will have significant impacts on food security (*medium evidence*, *medium agreement*). Recent experience of global climate patterns affecting food security indicates the potential nature and magnitude of increased variability. An impact assessment of the 2010 Pakistan floods surveyed 1800 households 6 months after the floods and found that 88% of the households reported income losses of up to 50%, with significantly higher rates in rural than urban areas (Kirsch et al., 2012). The same study indicated that loss of key services such as electricity, sanitation, and clean water resulted in lower standards of living even in the wake of significant relief attempts, again with significantly heavier effects on rural populations (Kirsch et al., 2012). The Russian heat wave of 2010 and subsequent export ban contributed to the more than doubling of global wheat prices by the end of the year. The degree to which these price increases affected domestic consumers and poverty depended on national responses in importing countries, although a significant net negative effect on poverty was found (Ivanic et al., 2011).

Increased incidence of climate extremes reduces incentives to invest in agricultural production, potentially offsetting positive impacts from increasing food price trends. This is particularly true for poor smallholders with limited or no access to credit and insurance. Greater exposure to climate risk, in the absence of well-functioning insurance markets, leads to (1) greater emphasis on low-return but low-risk subsistence crops (Roe and Graham-Tomasi, 1986; Fafchamps, 1992; Heltberg and Tarp, 2002), (2) a lower likelihood of applying purchased inputs such as fertilizer (Kassie et al., 2008; Dercon and Christiansen, 2011), (3) a lower likelihood of adopting new technologies (Feder et al., 1985; Antle and Crissman., 1990), and (4) lower investments (Skees et al., 1999). All of these responses generally lead to both lower current and future farm profits (*robust evidence*, *high agreement*) (Rosenzweig and Binswanger, 1993; Hurley, 2010).

It is also well documented that in many rural areas, smallholders in particular do not have the capacity to smooth consumption in the face of climate shocks, particularly generalized shocks that affect a majority of households in the same location (Dercon, 2004; Skoufias and Quisumbing, 2005; Dercon, 2006; Fafchamps, 2009; Prakash, 2011). Any increases in climate extremes will exacerbate the vulnerability of all food-insecure people, including smallholders (*robust evidence*, *high agreement*). Currently, smallholders rely to a large extent on increasing labor off-farm where possible (Fafchamps, 1999; Kazianga and Udry, 2006), but also by decreasing both food consumption and non-food expenditures, such as those on education and health care (*medium evidence*, *high agreement*; Skoufias and Quisumbing, 2005). Furthermore, some evidence also suggests that poorer households are more likely to reduce consumption, while wealthier households liquidate assets to cover current deficits (*limited evidence*, *medium agreement*; Kazianga and Udry, 2006; Carter and Lybbert, 2012). Reductions in food consumption, sales of productive assets, education, and health care can lead to long-term losses in terms of income generation and thus to future food security (*limited evidence*, *medium agreement*; Skoufias and Quisumbing, 2005; Hoddinot et al., 2008). Increased uncertainty of future climate conditions and increases in climate extremes will increase food insecurity unless these significant barriers to consumption and asset smoothing can be addressed (*medium evidence*, *medium agreement*).

7.3.3.2.3. Climate change impacts on utilization

Climate change impacts on utilization may come about through changes in consumption patterns in response to shocks, as well as changes in nutrient content of food as well as food safety (*medium evidence*, *medium agreement*). Rationing consumption to prioritize calorie-rich but nutrient-poor foods is another common response (Bloem et al., 2010). The effects are a decrease in dietary quality as well as quantity, which are magnified by pre-existing vulnerabilities—and lead to long-term loss of health, productivity capacity, and low incomes (*medium evidence*, *medium agreement*) (Alderman, 2010; Bloem et al., 2010; Brinkman et al., 2010; Campbell et al., 2010; Sari et al., 2010). The biological effects of climate change on nutrient content of foods are one of the main pathways for effects on utilization. A summary of recent literature on the impacts of climate change on the composition of nutrients in food items is given in HLPE (2012). Research on grains generally shows lowering of protein content with elevated temperature and CO_2 levels (Erda et al., 2005; Ainsworth and McGrath, 2010; Hatfield et al., 2011). There is good agreement that for plant-derived foods, mycotoxins are considered the key issue for food safety under climate change (Miraglia et al., 2009). The impacts of climate change on mycotoxins in the longer term are complex and region-specific; temperatures may increase sufficiently to eliminate certain mycotoxin-producing species from parts of the tropics but, in colder tropical regions and temperate zones, infections may increase (Cotty and Jaime-Garcia, 2007).

7.3.4. Sensitivity of Land Use to Weather and Climate

As noted in the AR4, changes in land use, for example, adjusting the location of crop production, are a potential adaptation response to climate change. Studies since the AR4 have confirmed that high-latitude locations will, in general, become more suitable for crops (Iqbal et al., 2009). Trnka et al. (2011), for example, examined projections of eleven agro-climatic indices across Europe, and found that declines in frost occurrence will lead to longer growing seasons, although temperature and moisture stress will often lead to greater interannual variability in crop suitability. The potential influence of pests and diseases is commonly beyond the scope of such studies (Gregory et al., 2009).

For tropical systems where moisture availability or extreme heat rather than frost limits the length of the growing season, there is a likelihood that the length of the growing season and overall suitability for crops will decline (*medium evidence*, *medium agreement*; Jones and Thornton, 2009; Zhang and Cai, 2011). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat stressed by the 2050s, while temperate wheat environments will expand northwards as climate changes (Ortiz et al., 2008). Similarly, by 2050, the majority of African countries will experience climates over at least half of their current crop area that lie outside the range currently experienced within the country (Burke et al., 2009). The majority of these novel climates have analogs in other African countries. In mountainous regions, where temperature varies significantly across topography, changes in crop suitability can be inferred from the variation of temperature across topography. The resulting vertical zones of increasing, decreasing, and unchanging suitability can be relatively robust in the face of uncertainty in future climate (Schroth et al., 2009).

The interaction between water resources and agriculture is expected to become increasingly important as climate changes. For example, whilst projected changes in crop productivity in China are uncertain, even within a single emissions scenario, irrigation has significant adaptation potential (Piao et al., 2010). However, limitations to availability of water will affect this potential. Changes in water use, including increased water diversion and development to meet increasing water demand,

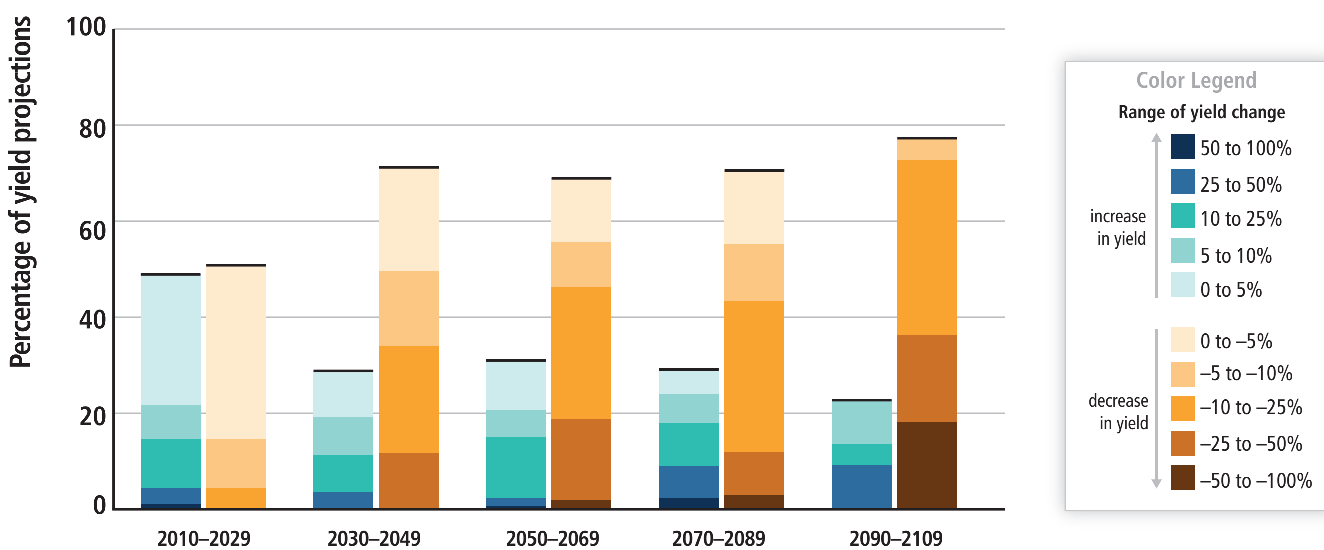


Figure 7-5 | Summary of projected changes in crop yields, due to climate change over the 21st century. The figure includes projections for different emission scenarios, for tropical and temperate regions, and for adaptation and no-adaptation cases combined. Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. For five timeframes in the near-term and long-term, data (n=1090) are plotted in the 20-year period on the horizontal axis that includes the midpoint of each future projection period. Changes in crop yields are relative to late-20th-century levels. Data for each timeframe sum to 100%. Projections taken from Abraha and Savage, 2006; Alexandrov and Hoogenboom, 2000; Arndt et al., 2011; Berg et al., 2013; Brassard and Singh, 2008; Brassard and Singh, 2007; Butt et al., 2005; Calzadilla et al., 2009; Chhetri et al., 2010; Ciscar et al., 2011; Deryng et al., 2011; Giannakopoulos et al., 2009; Hermans et al., 2010; Iqbal et al., 2011; Izaurralde et al, 2005; Kim et al., 2010; Lal, 2011; Li et al., 2011; Lobell et al., 2008; Moriondo et al., 2010; Müller et al., 2010; Osborne et al., 2013; Peltonen-Sainio et al., 2011; Piao et al., 2010; Ringler et al., 2010; Rowhanji et al., 2011; Schlenker and Roberts, 2009; Shuang-He et al., 2011; Southworth et al., 2000; Tan et al., 2010; Tao & Zhang, 2010; Tao and Zhang, 2011; Tao et al., 2009; Thornton et al., 2009; Thornton et al., 2010; Thornton et al., 2011; Tingem and Rivington, 2009; Tingem et al., 2008; Walker and Schulze, 2008; Wang et al., 2011; Xiong et al., 2007; Xiong et al., 2009.

and increased dam building will also have implications for inland fisheries and aquaculture, and therefore for the people dependent on them (Ficke et al., 2007; FAO, 2009a). In the case of the Mekong River basin, a large proportion of the 60 million inhabitants are dependent in some way on fisheries and aquaculture that will be seriously impacted by human population growth, flood mitigation, increased offtake of water, changes in land use, and overfishing, as well as by climate change (Brander, 2007). Ficke et al. (2007) reported that at that time there were 46 large dams planned or already under construction in the Yangtze River basin, the completion of which would have detrimental effects on those dependent on fish for subsistence and recreation.

The models used in projections of land suitability and cropland expansion discussed above rely on assumptions about non-climatic constraints on crop productivity, such as soil quality and access to markets. These assumptions are increasingly amenable to testing as the climate system shifts, by comparing observed changes in cropland area with model predictions. The location of the margin between cropping land and extensive grazing in southern Australia has varied with decadal climate conditions and is projected to shift toward the coast with hotter and drier conditions, notwithstanding the positive impacts of elevated CO_2 (Nidumolu et al., 2012). Recent trends in climate have seen reductions in cropping activity consistent with these projections (Nidumolu et al., 2012).

7.4. Projected Integrated Climate Change Impacts

7.4.1. Projected Impacts on Cropping Systems

Crop yields remain the most well studied aspect of food security impacts from climate change, with many projections published since AR4. These newer studies confirm many of the patterns identified in AR4, such as negative yield impacts for all crops past 3°C of local warming without adaptation, even with benefits of higher CO_2 and rainfall (Figure 7-4).

Figure 7-5 shows projected impacts on mean crop yield in 20-year bins, including cases with no adaptation and a range of incremental adaptations. The data indicate that negative impacts on average yields become *likely* from the 2030s. Negative impacts of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the century. Some important differences by emission scenario and region are masked in Figure 7-5. From the 2080s onwards, negative yield impacts in the tropics are *very likely*, regardless of adaptation or emission scenario. This is consistent with the meta-analysis of Knox et al. (2012), and a recent model intercomparison of global gridded crop models (Rosenzweig et al., 2013, 2014).

A few studies have explicitly compared projections for different regions or crops to identify areas at most risk. Lobell et al. (2008) used a statistical crop model with 20 GCMs and identified South Asia and southern Africa as two regions that, in the absence of adaptation, would suffer the most negative impacts on several important crops. Yields changes have also been assessed by regional meta-analyses: Knox et al. (2012) synthesized projections from 52 studies and estimated an expected 8% negative yield impact in both regions by 2050 averaged over crops, with wheat, maize, sorghum, and millets more affected than rice, cassava, and sugarcane.

Changes in the interannual variability of yields could potentially affect stability of food availability and access. Figure 7-6 shows projected changes in the coefficient of variation (CV) of yield from some of the few studies that publish this information. The data shown are consistent with reports of CV elsewhere: Müller et al. (2014) conducted gridded simulations across the globe and reported an increase of more than 5% in CV in 64% of grid cells, and a decrease of more than 5% in 29% of cases. Increases in CV can be due to reductions in mean yields and/or increases in standard deviation of yields, and often simulated changes are a combination of the two. Overall, climate change will increase crop yield variability in many regions (*medium evidence*, *medium agreement*).

Estimated impacts of both historical and future climate changes on mean yields are summarized along with projected impacts on yield variability in Figure 7-7, with all impacts expressed as the average percentage impact per decade. This comparison illustrates that future impacts are expected to be consistent with the trajectory of past impacts, with the majority of locations experiencing negative impacts while some locations benefit. Each additional decade of climate change is expected to reduce mean yields by roughly 1%, which is a small but nontrivial fraction of the anticipated roughly 14% increase in productivity per decade needed to keep pace with demand. For future projections, enough studies are available to assess differences by region and adaptation scenario, with significant adaptation effects apparent mainly in temperate systems (Section 7.5).

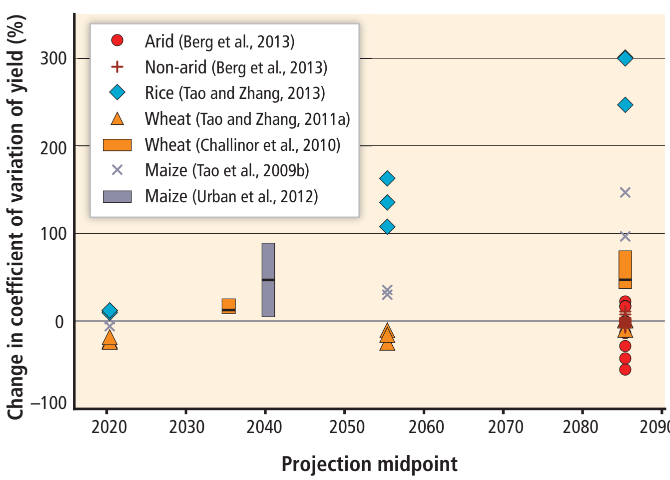


Figure 7-6 | Projected percentage change in coefficient of variation (CV) of yield for wheat (Tao and Zhang, 2011a; Challinor et al., 2010), maize (Tao et al., 2009b; Urban et al., 2012), rice (Tao and Zhang, 2013), and C_4 crops (arid and non-arid, Berg et al., 2013). The data from Urban et al. (2012) show the range (mean plus and minus one standard deviation) of percentage changes in CV. For the Challinor et al. (2010) data, paired CV changes were not available, so the box shows changes in the mean CV, the mean CV plus one standard deviation, and the mean CV minus one standard deviation. All other studies plot individual data points. A total of 81 data points are plotted in the figure, although the underlying data consist of many thousands of crop model simulations. The studies used a range of scenarios (Special Report on Emissions Scenarios (SRES) A1B, A2, A1FI, and B1). Berg et al. (2013) is a global study of the tropics, Urban et al. (2012) is for US maize, and the remaining data points are for China.

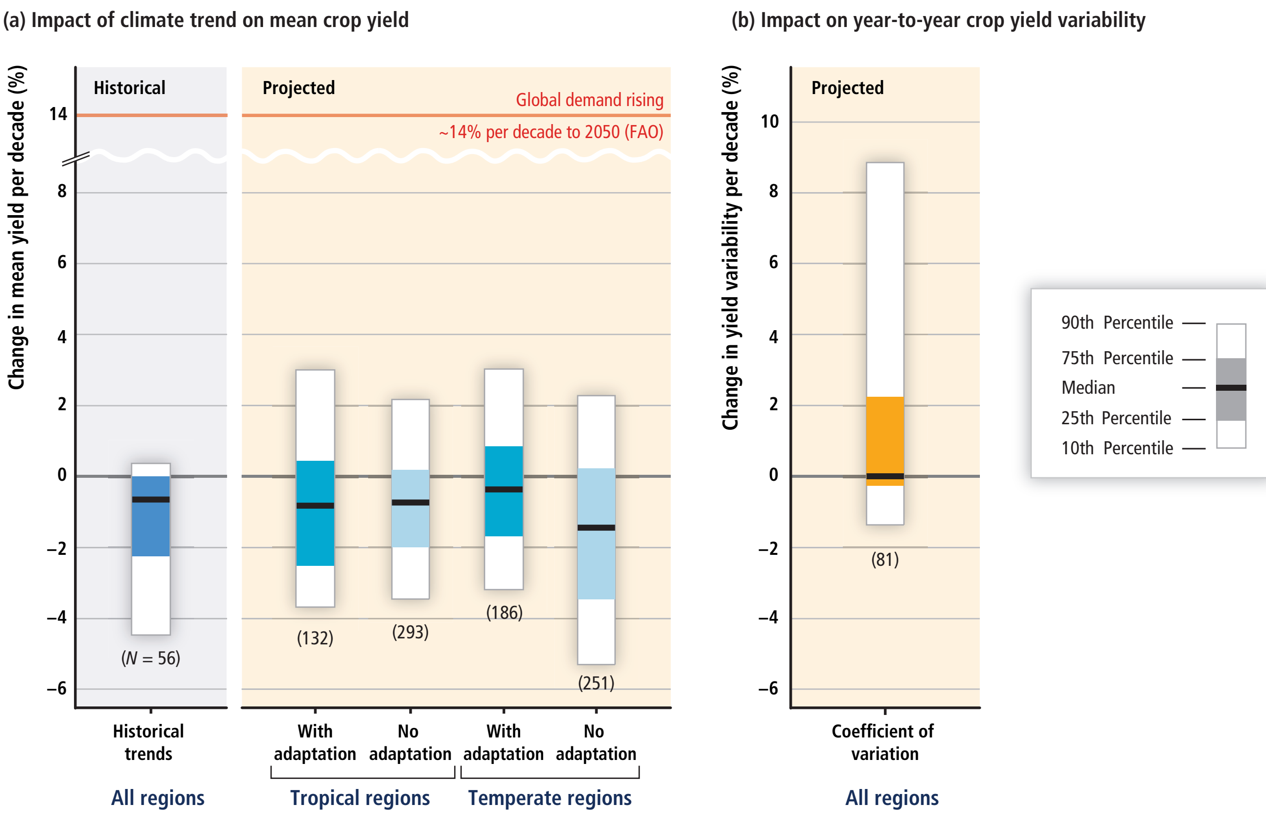


Figure 7-7 | Boxplot summary of studies that quantify impact of climate and CO_2 changes on crop yields, including historical and projected impacts, mean and variability of yields, and for all available crops in temperate and tropical regions. All impacts are expressed as average impact per decade (a 10% total impact from a 50-year period of climate change would be represented as 2% per decade). References for historical impacts are given in Figure 7-2, for projected mean yields in Figure 7-5, and for yield variability in Figure 7-6. *N* indicates the number of estimates, with some studies providing multiple estimates. In general, decreases in mean yields and increases in yield variability are considered negative outcomes for food security. Also indicated in the figure is the expected increase in crop demand of 14% per decade (Alexandratos and Bruinsma, 2012), which represents a target for productivity improvements to keep pace with demand.

Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more. An analysis for sub-Saharan Africa predicted overall decreases of 19% for maize yields, 68% decrease for bean yields, and a small increase for fodder grass (*Brachiaria decumbens*) given 5°C global average warming (Thornton et al., 2011). Rötter et al. (2011) conclude that positive effects of modest warming and increased CO_2 levels on crop yields in Finland will be reversed at global temperatures increases of 4°C, leading to negative yield impacts in excess of 20% in relation to current conditions.

For perennial crops, winter chill accumulation that is important to many fruit and nut trees is projected to continue its decline, with, for instance, a 40 chill-hours per decade reduction projected for California for the period up to 2100 (Baldocchi and Wong, 2008). Averaging over three GCMs, annual winter chill loss by 2050 compared to 1970 would amount 17.7% to 22.6% in Egypt (Farag et al., 2010). Several studies have projected negative yield impacts of climate trends for perennial trees, including apples in eastern Washington (Stöckle et al., 2010) and cherries in California (Lobell and Field, 2011), although CO_2 increases may offset some or all of these losses. Reductions in suitability for grapevine are expected in most of the wine-producing regions (Hall and Jones, 2009; White et al., 2009; Jones et al., 2010). Wine grape production and quality will be affected in Europe, USA, Australia (Jones et al., 2005; Wolfe et al., 2008; Cozzolino et al., 2010; Chapter 25), although it could be a benefit in Portugal (Santos et al., 2011) and British Columbia in Canada (Rayne et al., 2009). Important crops in Brazil such as sugarcane and coffee are expected to migrate toward more favorable zones in the South (Pinto, 2007; Pinto et al., 2008; Chapter 27). Sugarcane fresh stalk mass is generally expected to gain from both warming and elevated CO_2 in Brazil (Marin et al., 2013). The suitability for coffee crops in Costa Rica, Nicaragua, and El Salvador will be reduced by more than 40% (Glenn et al., 2013) while the loss of climatic niches in Colombia will force the migration of coffee crops toward higher altitudes by mid-century (Ramirez-Villegas et al., 2012). In the same way, increases in temperature will affect tea production, in particular at low altitudes (Wijeratne et al., 2007).

Consideration of pest, weed, and disease impacts are omitted from most yield projections, yet other studies have focused on projecting impacts of these biotic stressors. For pests and diseases, range expansion has been predicted for the destructive *Phytophthora cinnamomi* in Europe (Bergot et al., 2004) and for phoma stem canker on oilseed rape in the UK (Evans et al., 2008). Increased generations under climate change for the coffee nematode have been predicted for Brazil (Ghini et al., 2008). Walnut pests in California are predicted to experience increased numbers of generations under climate change scenarios (Luedeling et al., 2011). Luck et al. (2011) summarized the mixed results for the qualitative effects of climate change on pathogens that cause disease of four major food crops—wheat, rice, soybean, and potato—where some diseases increased in risk while others decreased under climate change scenarios. In syntheses, there is a tendency for risk of insect damage to plants to increase (Paulson et al., 2009). Typical scenario analyses are limited by simplistic assumptions, and work remains to evaluate how conclusions will change as more complete scenarios, such as those including migration and invasion patterns and other types of global change, are considered (Savary et al., 2005; Garrett et al., 2011). Effects on soil communities represent an area that needs more attention (Pritchard, 2011). Mycotoxins and pesticide residues in food are an important concern for food safety in many parts of the world, and identified as an important issue for climate change effects in Europe (Miraglia et al., 2009).

Weed populations and demographics are expected to change (*medium confidence*), with an overall poleward migration in response to warming (Ziska et al., 2011). An overview of crop and weed competitive studies indicate that weeds could limit crop yields to a greater extent with rising levels of CO_2 per se (Ziska, 2010). This may be related to the greater degree of phenotypic and genotypic plasticity associated with weedy species relative to the uniformity inherent in large cropping systems (Section 4.2.4.6). Chemical control of weeds, which is the preferred management method for large-scale farms, may become less effective (*limited evidence*, *medium agreement*), with increasing economic and environmental costs (Section 7.3.2.3).

Climate change effects on productivity will alter land use patterns, both in terms of total area sown to crops and the geographic distribution of that area. For example, the suitability for potato crops is expected to increase in very high latitudes and high tropical altitudes toward 2100 (Schaefleitner et al., 2011). Given expected trends in population, incomes, bioenergy demand, and agricultural technology, global arable area is projected to increase from 2007 to 2050, with projected increases over this period of +9% (Bruinsma, 2009), +8% (Fischer et al., 2009), +10 to 20% (Smith et al., 2010), and +18 to 23% (Lobell et al., 2013b) (*medium evidence*, *medium agreement*). Not all such studies included the effects of global warming. Where this is the case, estimates range from a 20% increase in cropping area to a decline of 9% (Zhang and Cai, 2011), but with large regional differences (*limited evidence*, *low agreement*). Countries at northern latitudes and under the current constraint of low temperature may increase cultivated area (*limited evidence*, *low agreement*). The generally lower nutrient quality of soils and the lack of necessary infrastructure required to convert virgin land into productive arable land make estimates of cropping area increases highly uncertain.

7.4.2. Projected Impacts on Fisheries and Aquaculture

Many studies have projected impacts of climate change on capture fisheries (Chapters 6 and 30) and only a subset of the more indicative studies at different ecological and geographical scales is included here. Overall, there is *high confidence* that climate change will impact on fisheries production with significant negative impacts particularly for developing countries in tropical areas, while more northerly, developed countries may experience benefits (Section 6.4.3).

Simulation studies on skipjack and bigeye tuna in the Pacific under both the Special Report on Emissions Scenarios (SRES) B1 and A2 scenarios indicate that catches of skipjack in the region as a whole are likely to increase by approximately 19% in 2035 compared to recent catch levels while catches of bigeye are projected to increase only marginally. By 2100, under the B1 scenario, catches of skipjack are projected to be 12.4% higher than recent levels but 7.5% lower under the A2 scenario, while catches of bigeye will be 8.8% and 26.7% lower under the B1 and A2 scenarios, respectively. The models indicate important regional differences, with a general trend that catches of tuna will decrease in the Western Pacific and increase in the Eastern Pacific (Lehodey et al., 2011; see also Sections 6.5.3, 30.6.2.1.1). These changes have important implications for the future of national fishing fleets and canneries in the Western Pacific (Bell et al., 2009). Climate change is expected to impact directly on the productivity of coastal fisheries in the Pacific island countries and territories through increased sea surface temperature and ocean acidification and indirectly through climate-driven damage to coral reefs, mangroves, seagrasses, and intertidal flats (Pratchett et al., 2011). Extreme events such as increased severity of tropical cyclones could also impact on some species. Under both B1 and A2 emissions scenarios, the vulnerability of coastal fisheries as a whole in 2035, as estimated through the framework described in Bell et al. (2009), is considered to be low. Extended to 2100, the projected impacts under the A2 emissions scenario are more severe, with reductions in coastal fisheries production by 20 to 35% in the west and 10 to 30% in the east (Pratchett et al., 2011).

Frequently Asked Questions

FAQ 7.2 | How could climate change interact with change in fish stocks and ocean acidification?

Millions of people rely on fish and aquatic invertebrates for their food security and as an important source of protein and some micronutrients. However, climate change will affect fish stocks and other aquatic species. For example, increasing temperatures will lead to increased production of important fishery resources in some areas but decreased production in others while increases in acidification will have negative impacts on important invertebrate species, including species responsible for building coral reefs that provide essential habitat for many fished species in these areas. The poorest fishers and others dependent on fisheries and subsistence aquaculture will be the most vulnerable to these changes, including those in Small Island Developing States, central and western African countries, Peru and Colombia in South America, and some tropical Asian countries.

Brown et al. (2010) project that, under the A2 emissions scenario, primary production in the ocean around Australia will increase over the 50-year period from 2000 to 2050 as a result of small increases in nutrient availability from changes in ocean stratification and temperature, although the authors acknowledge considerable model uncertainty. This increase is forecast, in general, to benefit fisheries catch and value. In a complementary study, Fulton (2011) used available end-to-end models to forecast the impacts of climate change under the A2 scenario across approximately two-thirds of Australia's exclusive economic zone. The results indicated that by 2060, the large-scale commercial fisheries, aided by their adaptive flexibility, would experience an overall increase of more than 90% in the value of their operations, although differing across sectors. The change in returns for the small-scale sector varied regionally from a decrease of 30 to 51% to a potential increase of 9 to 14%.

At the global scale, projections based on a dynamic bioclimatological envelope model under the SRES A1B scenario suggested that climate change could lead to an average 30 to 70% increase in fisheries yield from high-latitude regions (>50°N in the Northern Hemisphere), but a decrease of up to 40% in the tropics by 2055 compared to yields obtained in 2005 (Cheung et al., 2010). Another study using a suite of models linking physical, ecological, fisheries, and bioeconomic processes projected that, under the A1B scenario, the global yield from "large" fish could increase by 6% and that of the "small fish" used in fishmeal production by approximately 3.6%, assuming that marine fisheries and fish resources would be managed sustainably (Merino et al., 2012).

There is limited information available on projected impacts on food production in inland fisheries. Xenopoulus et al. (2005) investigated the effect of climate change and water withdrawal on freshwater fish extinctions under the assumptions of two scenarios consistent with scenarios A2 and B2. They forecast that discharge would increase in between 65 and 70% of river basins in the world but it would decrease by as much as 80% in 133 rivers for which fish species data were available. In the latter group, by 2070, up to 75% (quartile range, 4-22%) of the local fish biodiversity would be "headed toward extinction" because of changes in climate and water consumption, with the highest rates of extinction forecast mainly in tropical and subtropical areas. These results are not directly translatable into changes in fishery production but do give cause for concern for the likely affected areas (*limited evidence*, *low agreement*).

Information on future impacts on aquaculture is equally limited. Huppert et al. (2009) considered the impacts on the coast of Washington State, USA. They concluded that inundation of low-lying coastal areas from sea level rise, flooding from major storm events, and increased ocean temperatures and acidification would create significant challenges for the important shellfish aquaculture industry in the state. Inundation of existing shellfish habitats from sea level rise and increased incidence of harmful algal blooms were also contributory factors. Using a structured vulnerability framework and considering the B1 and A2 emission scenarios to project impacts on aquaculture in the tropical Pacific to 2035 and 2100, Pickering et al. (2011) concluded that production of freshwater species such as tilapia, carp, and milkfish will probably benefit from the expected climate changes, while coastal enterprises are expected to encounter problems in the same time horizons, varying according to species. Aquaculture production of calcifying organisms such as molluscs will experience loss of suitable habitats through ocean acidification. This will be particularly pronounced at and in the vicinity of eastern boundary upwelling systems (Section 30.6.2.1.4).

The food security consequences of the different impacts on capture fisheries and aquaculture are more difficult to estimate than the biological and ecological consequences. A preliminary study by Allison et al. (2009) examined the vulnerability of the economies of 132 countries to climate change impacts on fisheries in 2050 under the A1FI and B2 scenarios. Vulnerability was considered as a composite of three components: exposure to the physical effects of climate change, the sensitivity of the country to impacts on fisheries, and adaptive capacity within the country. This analysis suggested that under both scenarios several of the least developed countries were also among the most vulnerable to climate change impacts on their fisheries. They included countries in central and western Africa, Peru and Colombia in South America, and four tropical Asian countries.

7.4.3. Projected Impacts on Livestock

Climate change impacts on livestock will include effects on forage and feed, direct impacts of changes in temperature and water availability on animals, and indirect effects via livestock diseases. Many of the relevant processes and projected impacts for rangelands are discussed in Section 4.3.3.2, as well as in chapters for regions with prominent livestock sectors (Sections 22.3.4.2, 23.4.2, 25.7.2.1). In North American cattle systems, warming is expected to lengthen forage growing season but decrease forage quality, with important variations due to rainfall changes (Craine et al., 2010; Hatfield et al., 2011; Izaurralde et al., 2011). Simulations for French grasslands (Graux et al., 2013) and sown pastures in Tasmania (Perring et al., 2010) also project negative impacts on forage quality. Similarly, legume content of grasslands in most of southern Australia is projected to increase to the 2070s for SRES A2, with larger increases in wetter locations (Moore and Ghahramani, 2013).

There is *high confidence* that high temperatures tend to reduce animal feeding and growth rates (André et al., 2011; Renaudeau et al., 2011). The impacts of a changing UK climate on dairy cow production were analyzed by Wall et al. (2010), who showed that, in some regions, milk yields will be reduced and mortality increased because of heat stress throughout the current century, with annual production and mortality losses amounting to some £40 million by the 2080s under a medium-high GHG emission scenario.

Existing challenges of supplying water for an increasing livestock population will be exacerbated by climate change in many places (*limited evidence*, *high agreement*). For example, Masike and Urich (2008) project that warming under SRES A1 emission scenario will cause an annual increase of more than 20% in cattle water demand by 2050 for Kgatleng District, Botswana. At the same time, there is ample scope to improve livestock water productivity considerably (Molden et al., 2010); for example, in mixed crop-livestock systems of sub-Saharan Africa via feed, water, and animal management (Descheemaeker et al., 2010).

Host and pathogen systems in livestock will change their ranges because of climate change (*high confidence*). Species diversity of some

Box 7-1 | Projected Impacts for Crops and Livestock in Global Regions and Sub-Regions under Future Scenarios

Projected impacts for crops and livestock in global regions and sub-regions under future scenarios. Crop yield impacts in parentheses correspond to parentheticals in the scenario column. –CO_2 = without CO_2 effects; +CO_2 = with CO_2 effects; (I) = irrigated; (R) = rainfed. ARPEGE = Action de Recherche Petite Echelle Grande Echelle; CSIRO = Commonwealth Scientific and Industrial Research Organisation; ECHAM4 = European Centre for Medium Range Weather Forecasts Hamburg 4; GFDL-CM2.0/2 = Geophysical Fluid Dynamics Laboratory-Climate Model 2.0/2; HadCM3 = Met Office Hadley Centre Climate Prediction Model 3; HIRHAM = High-Resolution Hamburg Climate Model; MIROC = Model for Interdisciplinary Research On Climate; MPI-OM = Max Planck Institute; MRI-CGCM2.3.2 = Meteorological Research Institute of Japan Meteorological Agency-Coupled General Circulation Model 2.3.2; PRECIS = Providing Regional Climates for Impact Studies; RCA3 = Rossby Centre Regional Atmospheric Model 3.

Regional impacts on crops

Region	Sub-region	Yield impacts (%)	Scenario	Reference
World		• (I) Maize: –4, –7 • (R) Maize: –2, –12 • (I) Rice: –9.5, –12 • (R) Rice: –1, +0.07 • (I) Wheat: –10, –13 • (R) Wheat: –4, –10	A1B CSIRO, MIROC 2050	Nelson et al. (2010)
East Asia	China	(I) Maize: • –10.9 to –1.4 (–7.8 to –1.6), • –21.7 to –9.8 (–16.4 to –10.2), • –32.1 to –4.3 (–26.6 to –3.9) (R) Maize: • –22.2 to –1.0 (–10.8 to +0.7), • –27.6 to –7.9 (–18.1 to –5.6), • –33.7 to –4.6 (–25.9 to –1.6) (I) Rice: • –18.6 to –6.1 (–10.1 to +3.3), • –31.9 to –13.5 (–16.1 to +2.5), • –40.2 to –23.6 (–19.3 to +0.18)	+1°C, +2°C, +3°C –CO_2 (+CO_2)	Tao et al. (2011)
	Eastern China	Rice: • –10 to +3 (+7.5 to +17.5), • –26.7 to +2 (0 to +25), • –39 to –6 (–10 to + 25)	2030, 2050, 2080 –CO_2 (+CO_2)	Tao and Zhang (2013)
	Huang-Huai-Hai Plain, China	Wheat–maize: +4.5 ± 14.8, –5.8 ± 25.8	+2°C, +5°C	Liu et al. (2010)
	North China Plain	• (I) Wheat: –0.9 (+23) • (R) Wheat: –1.9 (+28)	A1B 2085–2100 –CO_2 (+CO_2) MIROC	Yang et al. (2013)
	Yangtze River, China	• (I) Rice: –14.8 (–3.3) • (R) Rice: –15.2 (–4.1)	B2 2021–2050 –CO_2 (+CO_2)	Shen et al. (2011)
South Asia	South Asia	• Maize: –16 • Sorghum: –11	2050	Knox et al. (2012)
	South Asia	Net cereal production –4 to –10	+3°C	Lal (2011)
	India	Winter sorghum: up to –7, –11, –32	A2 2020, 2050, 2080	Srivastava et al. (2010)
		• (I) Rice: –4, –7, –10 • (R) Rice: –6, –2.5, –2.5	A1B; A2; B1; B2 2020, 2050, 2080 +CO_2 MIROC; PRECIS/HadCM3	Kumar et al. (2013)
		• Monsoon maize: –21 to 0, –35 to 0, –35 to 0 • Winter maize: –13 to +5, –50 to +5, –60 to –21	A2 2020, 2050, 2080 HadCM3	Byjesh et al. (2010)
	Northeast India	• (I) Rice: –10 to +5 • (R) Rice: –35 to +5 • Maize: up to –40 • Wheat: up to –20	A1B 2030 +CO_2 PRECIS/HadCM3	Kumar et al. (2011)
	Coastal India	• (I) Rice: –10 to +5 • (R) Rice: –20 to +15 • (I) Maize: –50 to –15 • (R) Maize: –35 to +10		
	Western Ghats, India	• (I) Rice: –11 to +5 • (R) Rice: –35 to +35 • Maize: up to –50 • Sorghum: up to –50		
	Pakistan	Wheat: –7, –24 (Swat); +14, +23 (Chitral)	+1.5°C, +3°C	Section 24.4.4.3
		• Wheat: –6, –8 • Rice: –16, –19	B2, A2 2080	Iqbal et al. (2009)

Continued next page →

Box 7-1 (continued)

Region	Sub-region	Yield impacts (%)	Scenario	Reference
West Asia	Yarmouk Basin, Jordan	• Barley: –8, +5 • Wheat: –20, +18	–20%, +20% precipitation	Al-Bakri et al. (2010)
Africa	All regions	• Wheat: –17 • Maize: –5 • Sorghum: –15 • Millet: –10	2050	Knox et al. (2012)
	All regions	Maize: –24 ± 19	2090 +5ºC	Thornton et al. (2011)
	East Africa	• Maize: –3.1 to +15.0, –8.6 to +17.8 • Beans: –1.5 to +21.8, –18.1 to +23.7	A1FI; B1 2030, 2050 HadCM3; ECHam4	Thornton et al. (2010)
	Sahel	Millet: –20, –40	+2ºC, +3ºC	Ben Mohamed (2011)
Central & South America	Northeastern Brazil	• Maize: 0 to –10 • Wheat: –1 to –14 • Rice: –1 to –10	2030	Table 27-5; Lobell et al. (2008)
	Southern Brazil	• Maize: –15 • Bean: up to +45	A2 2080 $+CO_2$ HadCM3	Table 27-5; Costa et al. (2009)
	Paraguay	• Wheat: +4, –9, –13 (–1, +1, –5) • Maize: +3, +3, +8 (+3, +1, +6) • Soybean: 0, –10, –15 (0, –15, –2)	A2 (B2) 2020, 2050, 2080 PRECIS	Table 27-5; ECLAC (2010)
	Central America	• Wheat: –1 to –9 • Rice: 0 to –10	2030	Table 27-5; Lobell et al. (2008)
		• Maize: 0, 0, –10, –30 • Bean: –4, –19, –29, –87 • Rice: +3, –3, –14, –63	A2 2030, 2050, 2070, 2100	Table 27-5; ECLAC (2010)
	Panama	Maize: –0.5, +2.4, +4.5 (–0.1, –0.8, +1.5)	A2 (B1) 2020, 2050, 2080 $+CO_2$	Table 27-5; Ruane et al. (2013)
	Andean region	• Wheat: –14 to +2 • Barley: 0 to –13 • Potato: 0 to –5 • Maize: 0 to –5	2030	Table 27-5; Lobell et al. (2008)
	Chile	• Maize: –5% to –10% • Wheat: –10% to –20%	A1FI 2050 $+CO_2$ HadCM3	Table 27-5; Meza and Silva (2009)
	Argentina	• Wheat: –16, –11 (+3, +3) • Maize: –24, –15 (+1, 0) • Soybean: –25, –14 (+14, +19)	A2, B2 2080 $-CO_2$ ($+CO_2$) PRECIS	Table 27-5; ECLAC (2010)
North America	Midwestern United States	• Maize: –2.5 (–1.5) • Soy: +1.7 (+9.1)	+0.8ºC $-CO_2$ ($+CO_2$)	Hatfield et al. (2011)
	Southeastern United States	• Maize: –2.5 (–1.5) • Soy: –2.4 (+5.0)		
	United States Great Plains	Wheat: –4.4 (+2.4)		
	Northwestern United States	• Winter wheat: +19.5, +29.5 • Spring wheat: –2.2, –5.6	A1B 2040, 2080 $+CO_2$	Stöckle et al. (2010)
	Canadian prairies	• Small grains: –48 to +18 • Oilseeds: –50 to +25	+1ºC, +2ºC, +20% precipiation, –20% precipitation	Kulshreshtha (2011)
Europe	Boreal	Wheat, maize, soybean: +34 to +54	A2, B2 2080 HadCM3/HIRHAM, ECHAM4/RCA3	Iglesias et al. (2012)
	Alpine	Wheat, maize, soybean: +20 to +23		
	Atlantic North	Wheat, maize, soybean: –5 to +22		
	Atlantic Central	Wheat, maize, soybean: +5 to +19		
	Atlantic South	Wheat, maize, soybean: –26 to –7		
	Continental North	Wheat, maize, soybean: –8 to +4		
	Continental South	Wheat, maize, soybean: +11 to +33		
	Mediterranean North	Wheat, maize, soybean: –22 to 0		
	Mediterranean South	Wheat, maize, soybean: –27 to +5		

Continued next page →

Box 7-1 (continued)

Region	Sub-region	Yield impacts (%)	Scenario	Reference
Australia	South	Wheat: –15, –12	A2; Low, high plant available water capacity 2080 $+CO_2$ CCAM	Luo et al. (2009)
	Southeast	Wheat: –29 (–25)	B2, A2, A1FI 2080 $–CO_2$ ($+CO_2$) CCAM	Anwar et al. (2007)

Regional impacts on livestock

Region	Sub-region	Climate change impacts	Scenarios	Reference
Africa	Botswana	Cost of supplying water from boreholes could increase by 23% due to increased hours of pumping, under drier and warmer conditions.	A2, B2 2050	Section 22.3.4.2
	Lowlands of Africa	Reduced stocking of dairy cows, a shift from cattle to sheep and goats, due to high temperature.		
	Highlands of East Africa	Livestock keeping could benefit from increased temperature.		
	East Africa	Maize stover availability per head of cattle may decrease due to water scarcity.		
	South Africa	Dairy yields decrease by 10–25%.	A2 2046–2065/2080–2100 ECHAM5/MPI-OM, GFDL-CM2.0/2, MRI-CGCM2.3.2	Nesamvuni et al. (2012)
Europe	Netherlands	Dairy production affected at daily mean temperatures above 18ºC		Section 23.4.2
	Italy	Mortality risk to dairy cattle increased by 60% by exposure to high air temperature and high air humidity during breeding.		
	French Uplands	Annual grassland production system significantly reduced by 4-year exposure to climatic conditions.	A2 2070	Cantarel et al. (2013)
	France	No impact on dairy yields.	A2 1970–1999, 2020–2049, 2070–2099 ARPEGE	Graux et al. (2011)
	Ireland, France	Grassland dairy system increases potential of dairy production, with increased risk of summer–autumn forage failure in France.	A1B By the end of century	
	Overall Europe	Spread of bluetongue virus (BTV) in sheep and ticks in cattle due to climate warming.	2080	Graux et al. (2011)
		No increase in risk of incursion of Crimean–Congo hemorrhagic fever virus in livestock.		Section 23.4.2
Australia	Northern Australia	3ºC increase in temperature will result in 21% reduction in forage production for CO_2 at 350 ppm level and no change at 650 ppm level. Changes of ±10% in rainfall were exacerbated to ±15% change in forage production at 350 ppm CO_2.	A1B 2030	McKeon et al. (2009)
	Australia (other than Tasmania)	Dairy output will decline under 1ºC increase in temperature.	A1B 2030	Section 25.7.2.1
	25 sites in southern Australia	Profitability of fodder supply production declinedat most sites due to shorter growing season.	A2 2050	
	Southern Australia	Decline in NPP of grassland from historical climate will be 9% in 2030, 7% in 2050, and 14% in 2070. Declines in ANPP were larger at lower rainfall locations. Operating profit (at constant prices) fell by an average of 27% in 2030, 32% in 2050, and 48% in 2070.	A2 2030, 2050, 2070	Moore and Ghahramani (2013)
	Tasmania	Dairy yields increase 0.5–6.2%	A1B, ECHAM5/MPI-OM 2050	Hanslow et al. (2014)
	Victoria	Dairy yields decrease 1.3–6.7%		
	New South Wales	Dairy yields decrease 1.4–6.6%		
	Southern Australia	Dairy yields decrease 2.2–8.1%		
	New Zealand	Change in agricultural production: • Dairy: –2.8%, –4.3% • Sheep and beef: –6.1%, –8.8%	2030 Global temperature change 25%, 75% of the way between lower and upper bounds of scenarios in IPCC 2001 Third Assessment Report.	Wratt et al. (2008)

Continued next page →

Box 7-1 (continued)

Region	Sub-region	Climate change impacts	Scenarios	Reference
Central and South America	Andean Mountain countries	Beef and dairy cattle, pigs, and chickens could decrease between 0.9 and 3.2% while sheep could increase by 7%.	2060 Hot and dry scenario	Section 27.3.4.1
	Colombia, Venezuela, and Ecuador	Beef cattle choice declined.	2060 Milder and wet scenario	
	Argentina and Chile	Beef cattle choice increased.	Future climate change	
	Pernambuco, Brazil	Milk production and feed intake in cattle strongly affectetd.	Future climate change	Silva et al. (2009)
North America	Central United States	Dairy yields decrease 16–30%.	Baseline CO_2, 2× CO_2, 3× CO_2 CGCMI/Hadley	Mader et al. (2009)

pathogens may decrease in lowland tropical areas as temperatures increase (Mills et al., 2010). The temperate regions may become more suitable for tropical vector-borne diseases such as Rift Valley fever and malaria, which are highly sensitive to climatic conditions (Rocque et al., 2008). Vector-borne diseases of livestock such as African horse sickness and bluetongue may expand their range northward to the Northern Hemisphere because rising temperatures increase the development rate and winter survival of vectors and pathogens (Lancelot et al., 2008). Diseases such as West Nile virus and schistosomiasis are projected to expand into new areas (Rosenthal, 2009). The distribution, composition, and migration of wild bird populations that harbor the genetic pool of avian influenza viruses will all be affected by climate change, although in ways that are somewhat unpredictable (Gilbert et al., 2008). The changing frequency of extreme weather events, particularly flooding, will affect diseases too. For example, outbreaks of Rift Valley fever in East Africa are associated with increased rainfall and flooding due to ENSO events (Gummow, 2010; Pfeffer and Dobler, 2010). In general, the impacts of climate change on livestock diseases remain difficult to predict and highly uncertain (Mills et al., 2010; Tabachnick, 2010).

Box 7-1 summarizes impacts on a regional basis for crops and livestock. Developing countries rely heavily on climate-dependent agriculture and especially in conjunction with poverty and rapid increase in population they are vulnerable to climate change. While food insecurity is concentrated mostly in developing countries situated in the tropics (St. Clair and Lynch, 2010; Ericksen et al., 2011; Berg et al., 2013) global food supply may also be affected by heat stress in both temperate and subtropical regions (Teixeira et al., 2013). Chapter 22 identifies Africa as one of the regions most vulnerable to food insecurity. Climate change will also affect crop yields, food security, and local economies in Central America, northeast Brazil, and parts of the Andean region (Chapter 27) as well as in South Asia (Iqbal et al., 2009; see also Chapter 24). As shown in Box 7-1, in spite of uncertainties in responses at regional/national and subnational level, there is *high confidence* that most developing countries will be negatively affected by climate change in the future, although climate change may have positive effects in some regions. In high latitudes (such as Russia, northern Europe, Canada, South America) global warming may increase yields and expand the growing season and acreage of agricultural crops, although yields may be low due to poor soil fertility and water shortages in some regions (Kiselev et al., 2013; see also Chapters 23, 24, 26, 27). Although there is slim evidence, some studies do indicate a significant increase in crops yields in some parts of China, Africa, and India. Like crops, livestock are also negatively affected by climate change in almost all the continents, as evidenced by the regional chapters of Working Group II. The dairy, meat, and wool systems primarily rely on fodders, grasslands, and rangelands. Climate change can impact the amount and quality of produce, profitability, and reliability of production (Chapters 23, 25). Higher temperature would lead to decline in dairy production, reduced animal weight gain, stress on reproduction, increased cost of production, and lower food conversion efficiency in warm regions. Disease incidence among livestock is expected to be exacerbated by climate change as most of the diseases are transmitted by vectors such as ticks and flies (Chapter 23), whose proliferation depends on climatic parameters of temperature and humidity.

7.4.4. Projected Impacts on Food Prices and Food Security

AR4 presented a summary of food price projections based on five studies that used projected yield impacts as inputs to general or partial equilibrium models of commodity trade. Many additional projections of this type have been made since AR4, expanding the number of trade models used, the diversity of yield projections considered, and the disaggregation of prices by commodity (Hertel et al., 2010; Calzadilla et al., 2013; Lobell et al., 2013b; Nelson et al., 2013). Many of the studies did not include CO_2 effects, which is sometimes justified on the grounds that studies are concerned with "worst-case" scenarios, or that the bias from omitting positive CO_2 effects balances the known bias from omitting negative effects of elevated O_3 and increased weed and pest damage. Studies also typically ignore potential changes in yield variability (Figure 7-6) and policy responses such as export bans which have important international price effects (Section 7.2.2).

Based on the studies cited above, it is *very likely* that changes in temperature and precipitation, without considering effects of CO_2, will lead to increased food prices by 2050, with estimated increases ranging from 3 to 84%. The combined effect of climate and CO_2 change (but ignoring O_3 and pest and disease impacts) appears *about as likely as not* to increase prices, with a range of projected impacts from –30% to +45% by 2050. One lesson from recent model intercomparison experiments (Nelson et al., 2014) is that the choice of economic model matters at least as much as the climate or crop model for determining price response to climate change, indicating the critical role of economic uncertainties for projecting the magnitude of price impacts.

The AR4 concluded that climate changes are expected to result in higher real prices for food past 2050. This conclusion remains intact with *medium confidence*, albeit with a relative lack of new studies exploring price changes to 2100 or beyond. Of course, international prices are only one indicator of global food security, with the pathways by which price changes can affect food security outlined in Section 7.3.3. A limited number of studies have estimated the effects of price changes on food security and related health outcomes. Nelson et al. (2009) project that, without accelerated investment in planned adaptations, climate change by 2050 would increase the number of undernourished children under the age of 5 by 20 to 25 million (or 17 to 22%), with the range including projections with and without CO_2 fertilization. Lloyd et al. (2011) used the projected changes in undernourishment from Nelson et al. (2009) to project the impact of climate change on human nutrition, estimating a relative increase in moderate stunting of 1 to 29% in 2050 compared with a future without climate change. Severe stunting was projected to increase by 23% (central Africa) to 62% (South Asia).

In summary, if global yields are negatively impacted by climate change, an increase in both international food prices and the global headcount of food-insecure people is expected (*limited evidence*, *high agreement*). However, it is only *about as likely as not* that the net effect of climate and CO_2 changes on global yields will be negative by 2050, but *likely* that such changes will occur later in the 21st century. At the same time, it is *likely* that socioeconomic and technological trends, including changes in institutions and policies, will remain a relatively stronger driver of food security over the next few decades than climate change (Goklany, 2007; Parry et al., 2009). Importantly, all of the studies that project price impacts assume some level of on-farm agronomic adaptation, often by optimizing agronomic practices within the model. Most, but not all, also prescribe income growth rates as exogenous factors, despite the fact that incomes are heavily dependent on agriculture in many poor countries. One study that accounted for income effects found that, in countries such as Indonesia that had both a large share of poverty in agriculturally dependent households and yield impacts that were small relative to other regions, poverty was reduced by the effects of climate change (Hertel et al., 2010). However, in most countries the positive income effects of higher prices could not outweigh the costs of reduced productivity and higher food prices.

Recent work has also highlighted that productivity in many sectors besides agriculture are significantly influenced by warming, with generally negative effects of warming on economic output in tropical countries (Hsiang, 2010; Dell et al., 2012). Given the importance of incomes to food access, incorporating these effects into future estimates of food security impacts will be important. Conflict is also known to be an important factor in food security (FAO, 2010), and evidence of climate variability effects on conflict risk (Hsiang et al., 2011) indicates a need to also consider this dimension in future work (Chapter 12).

Since the impacts of climate change on food production and food security depends on multiple interacting drivers, the timing of extreme events, which are expected to become more frequent (IPCC, 2012), is critical. Extremes contribute to variability in productivity (Figure 7-6) and can form part of compound events that are driven by common external forcing (e.g., El Niño), climate system feedbacks, or causally unrelated events (IPCC, 2012). Such compound events, where extremes have simultaneous impacts in different regions, may have negative impacts on food security, particularly against the backdrop of increased food price volatility (Figure 7-3). There are very few projections of compound extreme events, and interactions between multiple drivers are difficult to predict. Effective monitoring and prediction, and building resilience into food systems, are likely to be two key tools in avoiding the negative impacts resulting from these interactions (Misselhorn et al., 2010).

7.5. Adaptation and Managing Risks in Agriculture and Other Food System Activities

7.5.1. Adaptation Needs and Gaps Based on Assessed Impacts and Vulnerabilities

7.5.1.1. Methods of Treating Impacts in Adaptation Studies—Incremental to Transformational

The pervasiveness of climate impacts on food security and production (Section 7.2), the commitment to future climate change from past GHG emissions (WGI AR5 SPM), and the very high likelihood of additional and likely greater climate changes from future GHG emissions (WGI AR5 SPM) mean that some level of adaptation of food systems to climate change will be necessary. Here we take adaptation to mean reductions in risk and vulnerability through the actions of adjusting practices, processes, and capital in response to the actuality or threat of climate change. This often involves changes in the decision environment, such as social and institutional structures, and altered technical options that can affect the potential or capacity for these actions to be realized. Adaptation can also enhance opportunities from climate change (WGII AR4 Chapter 5; Section 17.2.3). These adaptations will need to be taken in the context of a range of other pressures on food security such as increasing demand as a result of population growth and increasing per capita consumption (Section 7.1).

Following the AR4, the literature on adaptation and food production has increased substantially, although there has been less focus on adaptations to food systems and on value chains: the linked sets of activities that progressively add value as inputs are converted into products the market demands. Many adaptation frameworks or approaches have been published, informing the approach in the AR4 that addressed both autonomous and planned adaptations. Autonomous adaptations are incremental changes in the existing system including through the ongoing implementation of extant knowledge and technology in response to the changes in climate experienced. They include coping responses and are reactive in nature. Planned adaptations are proactive and can either adjust the broader system or transform it (Howden et al., 2010). Adaptations can occur at a range of scales from field to policy. There is an increasing recognition in the literature that while many adaptation actions are local and build on past climate risk management experience, effective adaptation will often require changes in institutional arrangements and policies to strengthen the conditions favorable for effective adaptation including investment in new technologies, infrastructure, information, and engagement processes (Sections 14.3-4, 15.2.4). Building adaptive capacity by decision makers at all scales (Nelson et al., 2008) is an increasingly important part of the adaptation discourse which has also further addressed costs, benefits, barriers, and limits of adaptation (Adger et al., 2009). The sector-specific nature of many adaptations means that sectors are initially addressed separately below.

7.5.1.1.1. Cropping

Effective adaptation of cropping could be critical in enhancing food security and sustainable livelihoods, especially in developing countries (WGII AR4 Chapter 5; Section 9.4.3.1). There is increasing evidence that farmers in some regions are already adapting to observed climate changes in particular altering cultivation and sowing times, crop cultivars and species, and marketing arrangements (Fujisawa and Koyabashi, 2010; Olesen et al., 2011; see also Section 9.4.3.1), although this response is not ubiquitous (Bryan et al., 2009). There are a large number of potential adaptations for cropping systems and for the food systems of which they are part, many of them enhancements of existing climate risk management and all of which need to be embedded in the wider farm systems and community contexts.

The possibility of extended growing seasons due to higher temperatures increasing growth in cooler months means that changing planting dates is a frequently identified option for cereals and oilseeds provided there is not an increase in drought at the end of the growing season (Krishnan et al., 2007; Deressa et al., 2009; Magrin et al., 2009; Mary and Majule, 2009; Meza and Silva, 2009; Tingem and Rivington, 2009; Travasso et al., 2009; Laux et al., 2010; Shimono et al., 2010; Stöckle et al., 2010; Tao and Zhang, 2010; Van de Geisen et al., 2010; Olesen et al., 2011; Cho et al., 2012). Aggregated across studies, changing planting dates may increase yields by a median of 3 to 17% but with substantial variation (Table 7-2). Early sowing is being facilitated by improvements in machinery and by the use of techniques such as dry sowing (Passioura and Angus, 2010), seedling transplanting, and seed priming and these adaptations can be integrated with varieties with greater thermal time requirements so as to maximize production benefits and to avoid late spring frosts (Tingem and Rivington, 2009; Cho et al., 2012). There can, however, be practical constraints to early sowing such as seedbed condition (van Oort et al., 2012). In some situations early sowing may allow double cropping or intercropping where currently only a single crop is feasible. For example, this could occur for irrigated maize in central Chile (Meza et al., 2008) and the double crop wheat/soybean in the southern pampas of Argentina (Monzon et al., 2007), increasing productivity per unit land although increasing nitrogen and water demand at the same time. However, in Mediterranean climates, early sowing of cereals is dependent on adequate planting rains in autumn and climate projections indicate that this may decrease in many regions (WGI AR5 SPM), limiting the effectiveness of this adaptation and possibly resulting in later sowings than are currently practiced. In such circumstances, use of short duration cultivars could be desirable so as to reduce exposure to end-of-season droughts and high-temperature events (Orlandini et al., 2008; Walter et al., 2010). There is *medium confidence* that optimization of crop varieties and planting schedules appears to be effective adaptations, increasing yields by up to 23% compared with current management when aggregated across studies (*medium evidence*, *high agreement*; Table 7-2). This flexibility in planting dates and varieties according to seasonal conditions could be increasingly important with ongoing climate change (Meza et al., 2008; Deressa et al., 2009) and especially in dealing with projections of increased climate variability (Figure 7-6). Approaches that integrate climate forecasts at a range of scales in some cases are able to better inform crop risk management (Cooper et al., 2009; Baethgen, 2010; Li et al., 2010; Sultana et al., 2010) although such forecasts are not always useable or useful (Lemos and Rood, 2010; Dilling and Lemos, 2011; see also Section 9.4.4).

Warmer conditions may also allow range expansion of cropping activities polewards in regions where low temperature has been a past limitation (*limited evidence*, *medium agreement*) provided varieties with suitable daylength response are available and soil and other conditions suitable. This may particularly occur in Russia, Canada, and the Scandinavian nations although the potential may be less than earlier analyses indicated

Frequently Asked Questions

FAQ 7.3 | How could adaptation actions enhance food security and nutrition?

More than 70% of agriculture is rain fed. This suggests that agriculture, food security, and nutrition are all highly sensitive to changes in rainfall associated with climate change. Adaptation outcomes focusing on ensuring food security under a changing climate could have the most direct benefits on livelihoods, which have multiple benefits for food security, including enhancing food production, access to markets and resources, and reduced disaster risk. Effective adaptation of cropping can help ensure food production and thereby contribute to food security and sustainable livelihoods in developing countries, by enhancing current climate risk management. There is increasing evidence that farmers in some regions are already adapting to observed climate changes, in particular altering cultivation and sowing times and crop cultivars and species. Adaptive responses to climate change in fisheries could include management approaches and policies that maximize resilience of the exploited ecosystems, ensuring fishing and aquaculture communities have the opportunity and capacity to respond to new opportunities brought about by climate change, and the use of multi-sector adaptive strategies to reduce the consequence of negative impacts in any particular sector. However, these adaptations will not necessarily reduce all of the negative impacts of climate change, and the effectiveness of adaptations could diminish at the higher end of warming projections.

Table 7-2 | The simulated median benefit (difference between the yield change from baseline for the adapted and non-adapted cases) for different crop management adaptations: cultivar adjustment; planting date adjustment; adjusting planting date in combination with cultivar adjustment; adjusting planting date in combination with other adaptations; irrigation optimization; fertilizer optimization; other management adaptations. N represents the number of estimates used for each adaptation. The numbers in parentheses are the 25th and 75th percentiles. Data points where assessed benefits of management changes are negative are not included as farmers are unlikely to adopt these intentionally. Only studies with both a "no adaptation" and an "adaptation" assessment are used. Data taken from Rosenzweig et al. (1994); Karim et al. (1996); El-Shaher et al. (1997); Lal et al. (1998); Moya et al. (1998); Yates and Strzepek (1998); Alexandrov (1999); Kaiser (1999); Reyenga et al. (1999); Southworth et al. (2000); Tubiello et al. (2000); DeJong et al. (2001); Aggarwal and Mall (2002); Alexandrov et al. (2002); Corobov (2002); Easterling et al. (2003); Matthews and Wasmann (2003); Droogers (2004); Howden and Jones (2004); Butt et al. (2005); Erda et al. (2005); Ewert et al. (2005); Gbetibouo and Hassan (2005); Xiao et al. (2005); Zhang and Liu (2005); Abraha and Savage (2006); Challinor et al. (2009); Tingem and Rivington (2009); Thornton et al. (2010); Deryng et al. (2011); Lal (2011); Tao and Zhang (2011b).

Management option	Cultivar adjustment (N = 56)	Planting date adjustment (N = 19)	Planting date and cultivar adjustment (N = 152)	Irrigation optimization (N = 17)	Fertilizer optimization (N = 10)	Other (N = 9)
Benefit (%) from using adaptation	23 (6.8, 35.9)	3 (2.1, 8.3)	17 (9.9, 26.1)	3.2 (2, 8.2)	1 (0.25, 4.8)	6.45 (3.2, 12.8)

owing to increased climate extremes, water limitations, and various institutional barriers (Alcamo et al., 2007; Bindi and Olesen, 2011; Dronin and Kirilenko, 2011; Kulshreshtha, 2011; Kvalvik et al., 2011; Tchebakova et al., 2011). In many of these cases, the northerly range expansion may only offset the reduction in southerly cropping areas and yields due to lower rainfall, water shortages, and high temperatures (*limited evidence*, *high agreement*).

Improving cultivar tolerance to high temperature is a frequently identified adaptation for almost all crops and environments worldwide as high temperatures are known to reduce both yield and quality (Krishnan et al., 2007; Challinor et al., 2009; Luo et al., 2009; Wassmann et al., 2009; Shimono et al., 2010; Stöckle et al., 2010), noting that a new cultivar usually takes between 8 and 20 years to deliver and so it is important to be selecting cultivars for expected future climate and atmospheric conditions (Ziska et al., 2012). Improving gene conservation and access to extensive gene banks could facilitate the development of cultivars with appropriate thermal time and thermal tolerance characteristics (Mercer et al., 2008; Wassmann et al., 2009) as well as to take advantage of increasing atmospheric CO_2 concentrations (Ziska et al., 2012) and respond to changing pest, disease, and weed threats with these developments needing to be integrated with *in situ* conservation of local varieties (IAASTD, 2009).

Similarly, the prospect of increasing drought conditions in many cropping regions of the world (Olesen et al., 2011) raises the need for breeding additional drought-tolerant crop varieties (Naylor et al., 2007; Mutekwa, 2009; Tao and Zhang, 2011a), for enhanced storage and access to irrigation water, more efficient water delivery systems, improved irrigation technologies such as deficit irrigation, more effective water harvesting, agronomy that increases soil water retention through practices such as minimum tillage and canopy management, agroforestry, increase in soil carbon, and more effective decision support (Verchot et al., 2007; Lioubimtseva and Henebry, 2009; Luo et al., 2009; Falloon and Betts, 2010; Piao et al., 2010; Olesen et al., 2011), among many other possible adaptations (Sections 22.4.2, 22.4.3). There is *medium confidence* (*limited evidence*, *high agreement*) that crop adaptations can lead to moderate yield benefits (mean of 10 to 20%) under persistently drier conditions (Deryng et al., 2011) and that irrigation optimization for changed climate can increase yields by a median of 3.2% (Table 7-2) as well as having a range of other beneficial effects (Section 3.7).

Diversification of activities is another climate adaptation option for cropping systems (Lioubimtseva and Henebry, 2009; Thornton et al., 2010). For example, Reidsma and Ewert (2008) found that regional farm diversity reduces the risk that is currently associated with unfavorable climate conditions in Europe. Diversification of activities often incorporates higher value activities or those that increase efficiency of a limited resource such as through increased water use efficiency (Thomas, 2008) or to reduce risk (Seo and Mendelsohn, 2008; Seo, 2010; Seo et al., 2010). In some cases, increased diversification outside of agriculture may be favored (Coulthard, 2008; Mary and Majule, 2009; Mertz et al., 2009a,b).

The above adaptations, either singly or in combination, could significantly reduce negative impacts of climate change and increase the benefit of positive changes as found in WGII AR4 Chapter 5 (*medium evidence*, *high agreement*). To quantify the benefits of adaptation, a meta-analysis of recent crop adaptation studies has been undertaken for wheat, rice, and maize (see Figure 7-4). This meta-analysis adds more recent studies to that undertaken in the WGII AR4 Chapter 5. It indicates that the average benefit (the yield difference between the adapted and non-adapted cases) of adapting crop management is equivalent to about 15 to 18% of current yields (Figure 7-8). This response is, however, extremely variable, ranging from negligible benefit from adaptation (even potential dis-benefit) to very substantial. The responses are dissimilar between wheat, maize, and rice (Figure 7-4) with temperate wheat and tropical rice showing greater benefits of adaptation. The responses also differ markedly between adaptation management options (Table 7-2). For example, when aggregated over studies, cultivar adaptation (23%) and altering planting date in combination with other adaptations (3 to 17%) provide on average more benefit than optimizing irrigation (3.2%) or fertilization (1%) to the new climatic conditions. These limits to yield improvements from agronomic adaptation and the increasingly overall negative crop yield impact with ongoing climate change (Figures 7-4, 7-5) mean a substantial challenge in ensuring increases in crop production of 14% per decade given a population of 9 billion people in 2050. This could be especially so for tropical wheat and maize, where impacts from increases in temperature of more than 3°C may more than offset benefits from agronomic adaptations (*limited evidence*, *medium agreement*).

Potential increased variability of crop production means that other climate-affected aspects of food systems such as food reserve, storage, and distribution policies and systems may need to be enhanced (IAASTD,

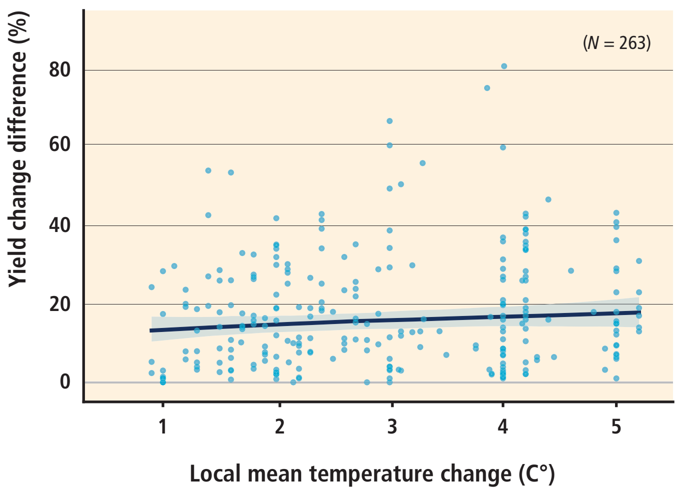


Figure 7-8 | Simulated yield benefit from adaptation calculated as the difference between the yield change from baseline (%) for paired non-adapted and adapted cases as affected by temperature and aggregated across all crops. The shaded bands at the 95% confidence interval are calculated as for Figure 7-4. Data points (N = 31) where assessed benefit of management changes are negative are not included as farmers are unlikely to intentionally adopt these. Data sources are the same as for Table 7-2 and only studies that examine both a "no adaptation" and an "adaptation" scenario are used so as to avoid the issues arising from unpaired studies documented in Figure 7-4 for tropical maize.

2009; Stathers et al., 2013) (*medium evidence*, *high agreement*) along with a range of broader, value-chain issues such as provision of effective insurance markets, clarity in property rights, building adaptive capacity, and developing effective participatory research cultures (Chapter 9; WGII AR4 Chapter 5).

It is notable that most of the above adaptations raised above and used in this analysis are essentially either incremental changes to existing agricultural systems or are systemic changes that integrate new aspects into current systems. Few could be considered to be transformative changes. Consequently, the potential adaptation benefits could be understated (*limited evidence*, *medium agreement*; Rickards and Howden, 2012).

7.5.1.1.2. Fisheries

Many of the resources for capture fisheries are already fully or overexploited, with an estimated 30% of stocks overexploited in 2009 and 57% fully exploited (FAO, 2012). Comparable global statistics are not available for inland fisheries but the status of those stocks may not be any better. Overfishing is widely regarded as the primary pressure on marine fishery resources but other human activities including coastal and offshore mining, oil and gas extraction, coastal zone development, land-based pollution, and other activities are also negatively impacting stock status and production (Rosenberg and Macleod, 2005; Cochrane et al., 2009). In inland fisheries, overfishing is also widespread, coupled with many other impacts from other human activities (Allan et al., 2005). Climate change adds another compounding influence in both cases.

Adaptive responses to reduce the vulnerability of fisheries and fishing communities could include management approaches and policies that strengthen the livelihood asset base; improved understanding of the existing response mechanisms to climate variability to assist in adaptation planning; recognizing and responding to new opportunities brought about by climate change; monitoring biophysical, social, and economic indicators linked to management and policy responses; and adoption of multi-sector adaptive strategies to minimize negative impacts (Allison et al., 2009; Badjeck et al., 2010; MacNeil et al., 2010). Complementary adaptive responses include occupational flexibility, changing target species and fishing operations, protecting key functional groups, and the establishment of insurance schemes (Coulthard, 2008; Daw et al., 2009; FAO, 2009a; MacNeil et al., 2010; Koehn et al., 2011). Fishers and fish farmers will be vulnerable to extreme events such as flooding and storm surges that will require a range of adaptations including developing early warning systems for extreme events, provision of hard defenses against flooding and surges, ensuring infrastructure such as ports and landing sites are protected, effective disaster response mechanisms, and others (Daw et al., 2009).

Governance and management of fisheries will need to follow an ecosystem approach to maximize resilience of the ecosystem, and to be adaptive and flexible to allow for rapid responses to climate-induced change (Daw et al., 2009; FAO, 2009a; see also Section 6.4.2). Within an ecosystem approach, habitat restoration will frequently be a desirable adaptation option, particularly in freshwater and coastal environments (Koehn et al., 2011). A wide range of management tools and strategies have been developed to manage fisheries. These are all necessary but not sufficient for adaptation to climate change in fisheries (Grafton, 2010). Grafton argued that the standard tools for fisheries management were developed to control fishing mortality and to maintain adequate levels of recruitment to fishery stocks but without necessarily addressing the needs for resilience to change or to be able to function under changing climates. He therefore proposed that these conventional management tools must be used within processes that (1) have a core objective to encourage ecosystems that are resilient to change and (2) explicitly take into account uncertainties about future conditions and the effect of adaptation, and make use of models to explore the implications of these (Grafton, 2010). There are also opportunities for fisheries to contribute to mitigation efforts (FAO, 2009a; Grafton, 2010).

Aquaculture is the fastest-growing animal-food-producing sector with per capita consumption of products increasing at an average rate of 7.1% per year between 1980 and 2010 (FAO, 2012). Adaptive responses in aquaculture include use of improved feeds and selective breeding for higher temperature tolerance strains to cope with increasing temperatures (De Silva and Soto, 2009) and shifting to more tolerant strains of molluscs to cope with increased acidification (Huppert et al., 2009). Better planning and improved site selection to adapt to expected changes in water availability and quality; integrated water use planning that takes into account the water requirements and human benefits of fisheries and aquaculture in addition to other sectors; and improving the efficiency of water use in aquaculture operations are some of the other adaptation options (De Silva and Soto, 2009).

Integrated water use planning will require making trade-offs between different land and water uses in the watershed (Mantua et al., 2010). Insurance schemes accessible to small-scale producers would help to increase their resilience (De Silva and Soto, 2009). In some near-shore locations there may be a need to shift property lines as the mean high water mark is displaced landwards by rising sea level (Huppert et al., 2009).

There are no simple, generic recipes for fisheries adaptation with Bell et al. (2011) suggesting a list of 25 separate but inter-related actions, together with supporting policies to adapt fisheries and aquaculture in the tropical Pacific to climate change (see also Section 30.6.2.1.1). These actions fall into three categories according to the primary objective: economic development and government revenue; maintaining the contribution of fish to food security; and maximizing sustainable livelihoods. Actions and policies for adaptation in fisheries and aquaculture must complement those for other sectors. Similar case-by-case, integrated planning will be required in all other regions and at scales from community to regional to achieve clearly defined adaptation goals.

7.5.1.1.3. Livestock

Extensive livestock systems occur over a huge range of biophysical and socio-ecological systems, with a consequent large range of potential adaptations. In many cases, these livestock systems are highly adapted to past climate risk, and there is *high confidence* that this provides a sound starting point for climate change adaptation (*medium evidence, high agreement*; Thornton et al., 2009a). These adaptations include matching stocking rates with pasture production; adjusting herd and watering point management to altered seasonal and spatial patterns of forage production; managing diet quality (using diet supplements, legumes, choice of introduced pasture species and pasture fertility management); more effective use of silage, pasture spelling, and rotation; fire management to control woody thickening; using more suitable livestock breeds or species; migratory pastoralist activities; and a wide range of biosecurity activities to monitor and manage the spread of pests, weeds, and diseases (Fitzgerald et al., 2008; Howden et al., 2008; Nardone et al., 2010; Ghahramani and Moore, 2013; Moore and Ghahramani, 2013). Combining adaptations can result in substantial increases in benefits in terms of production and profit when compared with single adaptations (Ghahramani and Moore, 2013; Moore and Ghahramani, 2013). In some regions, these activities can in part be informed by climate forecasts at differing time scales to enhance opportunities and reduce risks including soil degradation (McKeon et al., 2009). Many livestock systems are integrated with or compete for land with cropping systems and one climate adaptation may be to change these relationships. For example, with increased precipitation, farmers in Africa may need to reduce their livestock holdings in favor of crops, but with rising temperatures, they may need to substitute small ruminants in place of cattle with small temperature increases or reduce stocking rates with larger temperature rises (Kabubo-Mariara, 2009; Thornton et al., 2010). As with other food systems there is a range of barriers to adaptation that could be addressed on-farm and off-farm by changes in infrastructure, establishment of functioning markets, improved access to credit, improved access to water and water management technologies, enhanced animal health services, and enhanced knowledge adoption and information systems (Howden et al., 2008; Kabubo-Mariara, 2008; Mertz et al., 2009b, Silvestri et al., 2012).

Heat stress is an existing issue for livestock in some regions (*robust evidence*, *high agreement*), especially in higher productivity systems (Section 7.3.2.6). For example, some graziers in Africa are already making changes to stock holdings in response to shorter term variations in temperatures (Thornton et al., 2009a; see also 9.4.3.1). Breeding livestock with increased heat stress resistance is an adaptation often identified but there are usually trade-offs with productivity as well as benefits including animal welfare and so this option needs careful evaluation (Nardone et al., 2010). Increased shade provision through trees or cost-effective structures can substantially reduce the incidence of high heat stress days, reduce animal stress, and increase productivity, with spraying a less effective option (Gaughan et al., 2010; Nidumolu et al., 2013). In cooler climates, warming may be advantageous because of lesser need for winter housing and feed stocks.

7.5.1.1.4. Indigenous knowledge

Indigenous knowledge (IK) has developed to cope with climate hazards contributing to food security in many parts of the world. Examples in the Americas include Alaska, where the Inuit knowledge of climate variability ensured the source of food to hunters and reduced various risks (Alessa et al., 2008; Ford, 2009; Weatherhead et al., 2010) down to the southern Andes, where the Inca traditions of crop diversification, genetic diversity, raised bed cultivation, agroforestry, weather forecasting, and water harvesting are still used in agriculture (Goodman-Elgar, 2008; Renard et al., 2011; McDowell and Hess, 2012; see also Sections 9.4.3.1, 27.3.4.2). In Africa, weather forecasting, diversity of crops and agropastoralism strategies have been useful in the Sahel (Nyong et al., 2007). Rainwater harvesting has been a common practice in sub-Saharan Africa (Biazin et al., 2012) to cope with dry spells and improve crop productivity, while strategies from agropastoralists in Kenya are related to drought forecasting based on the fauna, flora, moon, winds, and other factors (Speranza et al., 2010). In South Africa, farmers' early warming indicators of wet or dry periods in Namibia based on animals, plants, and climate observations contributed to deal with climatic variability (Newsham and Thomas, 2011). In the same way, in Asia and Australia IK plays an important role to ensure food security of certain groups (Salick and Ross, 2009; Green et al., 2010; Marin, 2010; Speranza et al., 2010; Kalanda-Joshua et al., 2011; Pareek and Trivedi, 2011; Biazin et al., 2012), although IK and the opportunities to implement it can differ according to gender and age in some communities (Rengalakshmi, 2007; Turner and Clifton, 2009; Kalanda-Joshua et al., 2011; see also Section 9.3.5), leading to distinct adaptive capacities and options.

In addition to changes already occurring in climate (seasonal changes, changes in extreme events; IPCC 2012) projected changes beyond historical conditions could reduce the reliance on indigenous knowledge (Speranza et al., 2010; Kalanda-Joshua et al., 2011; McDowell and Hess, 2012) affecting the adaptive capacity of a number of peoples globally (*medium evidence*, *medium agreement*).

Moreover, there is *medium confidence* that some policies and regulations leading to limit the access to territories, promoting sedentarization, the substitution of traditional livelihoods, reduced genetic diversity and harvesting opportunities, as well as loss of transmission of indigenous knowledge, may contribute to limit the adaptation to climate change in many regions (*medium evidence*, *medium agreement*; Nakashina et al., 2012).

7.5.1.2. Practical Regional Experiences of Adaptation, Including Lessons Learned

Given the early stages of climate change, there are relatively few unequivocal examples of adaptation (Section 7.5.2) additional to existing climate risk management. Where there have been management changes these have often been in response to several driving variables of which climate is only one (Smit and Wandel, 2006; Mertz et al., 2009a; Chen et al., 2011; Odgaard et al., 2011; see also Section 9.4.3.1). The preparedness to consider adaptation even within an industry varies regionally (Battaglini et al., 2009) and in some regions there already appears to be adaptation to climate change occurring (Fujisawa and Koyabashi, 2010; Olesen et al., 2011; Bohensky et al., 2012; Section 9.4.3.1). Activities to build adaptive capacity to better manage climate change are more widespread (Twomlow et al., 2008) but there remain questions as to how this capacity will evolve and be maintained (Nelson et al., 2009). Crucial in this will be devolution of the decision-making process so as to integrate local, contextual information into adaptation decision making (Nelson et al., 2008).

7.5.1.3. Observed and Expected Barriers and Limits to Adaptation

Adaptation is strongly influenced by factors including institutional, technological, informational, and economic and there can be barriers (restrictions that can be addressed) and limits in all these factors (*robust evidence*, *high agreement*; Chapters 14, 15, 16). Several barriers to adaptation of food systems have been raised including inadequate information on the climate and climate impacts and on the risks and benefits of the adaptation options, lack of adaptive capacity, inadequate extension, institutional inertia, cultural acceptability, financial constraints including access to credit, insufficient fertile land, infrastructure, lack of functioning markets, and insurance systems (Bryan et al., 2009; Deressa et al., 2009; Kabubo-Mariara, 2009; De Bruin and Dellink, 2011, Silvestri et al., 2012; see also Chapter 16). Limits to adaptation can occur for example where crop yields drop below the level required to sustain critical infrastructure such as sugar or rice mills (Park et al., 2012). In some cases, these can be effectively irreversible. Some studies have shown that access to climate information is not the principal limitation to improving decision making and it can result in perverse outcomes, increasing inequities and widening gender gaps (Coles and Scott, 2009). Incomplete adoption of adaptations may also occur. Lack of technical options can also be a barrier to adaptation. New varieties of crops or breeds of livestock provide possible core adaptations of production systems (*medium evidence*, *high agreement*; Mercer et al., 2008; Tingem and Rivington, 2009); however, there is substantial investment needed to develop these along with delays before they are available, both of which can act as adaptation barriers. This may be addressed in part by investments to improve local crop varieties or livestock breeds that are easily adopted (IAASTD, 2009). There also can be physiological limits to performance such as upper temperature limits for heat tolerance (WGII AR4 Chapter 5).

7.5.1.4. Facilitating Adaptation and Avoiding Maladaptation

Adaptation actions would usually be expected to provide benefits to farmers, the food industry along the value chain, or perhaps to a broader community. However, there are possible maladaptations that arise from adapting too early or too late, by changing the incorrect elements of the food system or changing them by the incorrect amount (Section 14.7). A key maladaptation would be one which increased emissions of GHGs, this making the underlying problem worse (*robust evidence*, *high agreement*; Smith and Olesen, 2010; WGIII AR4 Chapter 11). A recent review of agricultural climate change adaptation options found they tend to reduce GHG emissions (Smith and Olesen, 2010; Falloon and Betts, 2010) (*medium evidence*, *medium agreement*). These adaptations include measures that reduce soil erosion and loss of nutrients such as nitrogen and phosphorus and for increasing soil carbon, conserving soil moisture, and reducing temperature extremes by increasing vegetative cover. There is a strong focus on incremental adaptation of existing food systems in the literature since AR4, however, and this may result in large opportunity costs that could arise from not considering more systemic adaptation or more transformative change (*limited evidence*, *medium agreement*; Howden et al., 2010; Kates et al., 2012). For example, in the USA, changes in farming systems (i.e., the combination of crops) have been assessed as providing significant adaptation benefit in terms of net farm income (Prato et al., 2010) although in other regions this might be minor (Mandryk et al., 2012). There is a need to also engage farmers, policymakers, and other stakeholders in evaluating transformative, pro-active, planned adaptations such as structural changes (Mäder et al., 2006; McCrum et al., 2009; Olesen et al., 2011). This could involve changes in land allocation and farming systems, breeding of functionally different crop varieties, new land management techniques, and new classes of service from lands such as ecosystem services (Rickards and Howden, 2012). In Australia, industries including the wine, rice, and peanut sectors are already attempting transformative changes such as change in location so as to be early adopters of what are perceived as opportunities arising from change (Park et al., 2012). There is substantial commonality in adaptation actions within different agricultural systems. For example, changing varieties and planting times are incremental adaptations found in studies of many different cropping systems as evidenced by the sample size in the meta-analysis in this chapter. Collating information on the array of adaptation options available for farmers, their relative cost and benefit, and their broad applicability could be a way of initiating engagement with decision makers. In the climate mitigation domain, this has been attempted using marginal abatement cost curves that identify mitigation options, their relative cost, and the potential size of emission reductions (WGIII AR4 Chapter 11). These curves can be used in setting investment priorities and informing policy discussions. The local nature of many adaptation decisions, their interactions with other highly contextual driving factors, and the time and climate change-sensitive nature of adaptation decisions mean, however, that global, time-independent curves are not feasible. The studies aggregated in Table 7-2 indicate that some options may be more relevant and useful to consider than others. These results illustrate the potential scope and benefit of developing effective adaptation options if implemented in an adaptive management approach.

7.5.2. Food System Case Studies of Adaptation—Examples of Successful and Unsuccessful Adaptation

Incremental, systemic, and transformational adaptation to climate change is beginning to be documented, though the peer-reviewed literature largely covers vulnerability assessments and intentions to act, not adaptation actions (Berrang-Ford et al., 2010).

Case 1: Incremental Adaptation in the Sahel

Much of the literature covers incremental, reactive adaptation, but given actors are constantly adapting to changing social and economic conditions, incremental adaptation to climate change is difficult to distinguish from other actions (Berrang-Ford et al., 2010; Speranza et al., 2010), and in fact is usually a response to a complex of factors. This case, of the zaï soil management practice in the Sahel region, is an example of a complex of factors driving local actions, and factors such as growing land scarcity and new market opportunities, rather than climate, may be the primary factors (Barbier et al., 2009; Mertz, 2009b). Inherent poor soil quality and human activities have resulted in soil degradation—crusting, sealing, erosion by water and wind, and hardpan formation (Fatondji et al., 2009; Zougmoré et al., 2010). Zaï, a traditional integrated soil and water management practice, can combat land degradation and improve yield and decrease yield variability by concentrating runoff water and organic matter in small pits (20 to 40 cm in diameter and 10 to 15 cm deep) dug manually during the dry season and combined with contour stone bunds to slow runoff. A handful of animal manure or compost is placed in each pit. By breaking the soil crust, the pits facilitate greater water infiltration, while the applied organic matter improves soil nutrient status and attracts termites, which have a positive effect on soil structure. The zaï technique is very labor intensive, requiring some 60 days of labor per hectare. Innovations to the system, involving animal-drawn implements, can reduce labor substantially.

Case 2: Mixed Farming Systems in Tanzania

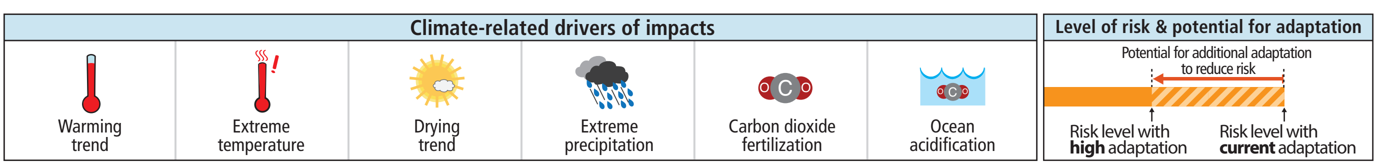
In Morogoro, Tanzania, farming households have adapted in many ways to climatic and other stresses (Paavola, 2008). They have extended cultivation through forest clearance or reducing the length of the fallow period. Intensification is under way, through change in crop choices, increased fertilizer use and irrigation, and especially greater labor inputs. Livelihood diversification has been the main adaptation strategy—this has involved more non-farm income-generating activities, tapping into natural resources for subsistence and cash income (e.g., charcoal production), and has included artisanal gold and gemstone mining. Households have also altered their cropping systems, for example, by changing planting times. Migration is another frequently used strategy—with farmers moving to gain land, access to markets, or employment. Parents also send children to cities to work for upkeep and cash income to reduce the household numbers that need to be supported by uncertain agricultural income. While many of these strategies help in terms of the short-term needs, in the longer term they may be reducing the capacity of households to cope. For instance, land cover change interacting with climate changes has negative impacts on current and future water supplies for irrigation (Natkhin et al., 2013), and deforestation and forest degradation means faltering forest-based income sources. This will be particularly problematic to the more vulnerable groups in the community, including women and children.

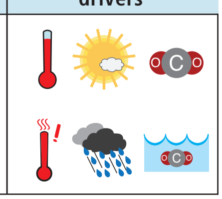
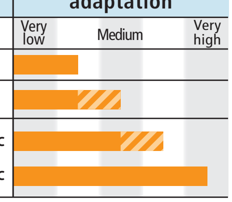
7.5.3. Key Findings from Adaptations—Confidence Limits, Agreement, and Level of Evidence

There have been many studies of crop adaptation since the AR4. In aggregate these show that adaptations to changed temperature and precipitation will bring substantial benefit (*robust evidence*, *high agreement*), with some adaptations (e.g., cultivar adaptation and planting date adjustment) assessed as on average being more effective than others (e.g., irrigation optimization; Section 7.5.1.1.1). Most studies have assessed key farm-level adaptations such as changing planting dates and associated decisions to match evolving growing seasons and improving cultivar tolerance to high temperature, drought conditions, and elevated CO_2 levels. Limits to adaptation will increasingly emerge for such incremental adaptations as the climate further changes, raising the need for more systemic or transformational changes (*limited evidence*, *medium agreement*; Section 7.5.1.1). An example of transformational change is latitudinal expansion of cold-climate cropping zones polewards, but this may be largely offset by reductions in cropping production in the mid-latitudes as a result of rainfall reduction and temperature increase (*medium confidence*, *limited evidence*; Section 7.5.1.1.1). Adaptations to food systems additional to the production phase have been identified and sometimes implemented but the benefits of these have largely not been quantified.

Livestock and fisheries systems also have available a large range of possible adaptations often tailored to local conditions but there is not adequate information to aggregate the possible value of these adaptations although there is *high confidence* (*medium evidence*, *high agreement*) that they will bring substantial benefit, particularly if implemented in

Table 7-3 | Schematic key risks for food security and the potentials for adaptation in the near and long term for high and low levels of warming.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Reductions in mean crop yields because of climate change and increases in yield variability. (*high confidence*) [7.2, 7.3, 7.4, 7.5, Box 7-1]	With or without adaptation, negative impacts on average yields become *likely* from the 2030s with median yield impacts of 0 to –2% per decade projected for the rest of the century, and after 2050 the risk of more severe impacts increases.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	

combination (Sections 7.5.1.1.2-3). Key livestock adaptations include matching stocking rates with pasture availability; water management; monitoring and managing the spread of pests, weeds, and diseases; livestock breeding; and adjusting to changed frequencies of heat stress and cold conditions (Section 7.5.1.1.3). Fishery adaptations include management approaches and policies that strengthen the livelihood asset base, take a risk-based ecosystem approach to managing the resource, and adopt multi-sector adaptive strategies to minimize negative impacts. Importantly, there is an emerging recognition that existing fishery management tools and strategies are necessary but not sufficient for adaptation to climate (Section 7.5.1.1.2).

Indigenous knowledge is an important resource in climate risk management and is important for food security in many parts of the world. Climate changes may be reducing reliance on indigenous knowledge in some locations but also some policies and regulation may be limiting the contribution that indigenous knowledge can make to effective climate adaptation (*medium evidence*, *medium agreement*; Section 7.5.1.1.4).

The focus on incremental adaptations and few studies on more systemic and transformational adaptation or adaptation across the food system mean that there may be underestimation of adaptation opportunities and benefits (*limited evidence*, *medium agreement*; Section 7.5.1.1). In addition to this, there is a range of limits and barriers to adaptation and many of these could be addressed by devolution of the decision-making process so as to integrate local, contextual information into adaptation decision making. A schematic summary of these issues is given in Table 7-3.

7.6. Research and Data Gaps—Food Security as a Cross-Sectoral Activity

Research and data gaps reflect that most work since AR4 has continued to concentrate on food production and has not included other aspects of the food system that connect climate change to food security. Features such as food processing, distribution, access, and consumption have recently become areas of research interest in their own right but only tangentially attached to climate change.

Many studies either do not examine yield variability or do not report it. Closer attention should be paid to yield variability in the quantity and quality of food production, especially given observed price fluctuations associated with climate events. We expect environmental thresholds and tipping points, such as high temperatures, droughts, and floods, to become more important in the future. Specific recommendations are for food production experiments in which changes in variability reflect predicted changes for given warming scenarios. Including thresholds in impact models, for especially high levels of global warming (i.e., 4 to 6°C above preindustrial), are highly likely to result in lower projections of yield, given changes in climate variability and increasing mean temperatures. Important gaps in knowledge continue to be studies of weeds, pests, and diseases, including animal diseases, in response to climate change and how related adaptation activities can be robustly incorporated into food security assessments. Yield and other agronomic data, at a range of spatial scales, are crucial to the development, evaluation, and improvement of models. Model development is currently limited by lack of data.

Adaptation studies for cropping systems typically assess relatively minor agronomic management changes under future climate conditions only. Forthcoming studies should examine the impact of proposed adaptations when employed in the current climate. In this way management changes that are beneficial in a range of environments can be separated from management changes that are specifically targeted at climate change. Further, studies should be inclusive of the broader range of systemic and transformational adaptation options open to agriculture.

Current forecasts of changes in distribution and productivity of marine fish species and communities are typically at a global or regional scale and include adaptations to only a limited extent. Increasing the resolution to forecast impacts and changes at the national and local ecosystem scale would provide valuable information to governments and stakeholders and enable them to prepare more effectively for expected impacts on food production and security offered by fisheries.

Possibilities for agronomic and breeding adaptations of food production to global warming are possible up to high levels of climate change. However, food security studies are urgently required to estimate the actual range of adaptations open to farmers and other actors in the food system and the implementation paths for these, especially when possible changes in climate variability are included.

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8 Urban Areas

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Executive Summary

Urban climate adaptation can build resilience and enable sustainable development. {8.1, 8.2, 8.3}

Action in urban centers is essential to successful global climate change adaptation. Urban areas hold more than half the world's population and most of its built assets and economic activities. They also house a high proportion of the population and economic activities most at risk from climate change, and a high proportion of global greenhouse gas emissions are generated by urban-based activities and residents (*medium confidence*, based on *medium evidence*, *high agreement*). {8.1}

Much of key and emerging global climate risks are concentrated in urban areas. Rapid urbanization and rapid growth of large cities in low- and middle-income countries have been accompanied by the rapid growth of highly vulnerable urban communities living in informal settlements, many of which are on land at high risk from extreme weather (*medium confidence*, based on *medium evidence*, *high agreement*). {8.2, 8.3, Tables 8-2, 8-3}

Cities are composed of complex inter-dependent systems that can be leveraged to support climate change adaptation via effective city governments supported by cooperative multilevel governance. This can enable synergies with infrastructure investment and maintenance, land use management, livelihood creation, and ecosystem services protection (*medium confidence*, based on *limited evidence*, *medium agreement*). {8.3, 8.4}

Urban adaptation action that delivers mitigation co-benefits is a powerful, resource-efficient means to address climate change and to realize sustainable development goals (*medium confidence*, based on *medium evidence*, *high agreement*). {8.4}

Urban climate change risks, vulnerabilities, and impacts are increasing across the world in urban centers of all sizes, economic conditions, and site characteristics. {8.2}

Urban climate change-related risks are increasing (including rising sea levels and storm surges, heat stress, extreme precipitation, inland and coastal flooding, landslides, drought, increased aridity, water scarcity, and air pollution) with widespread negative impacts on people (and their health, livelihoods, and assets) and on local and national economies and ecosystems (*very high confidence*, based on *robust evidence*, *high agreement*). These risks are amplified for those who live in informal settlements and in hazardous areas and either lack essential infrastructure and services or where there is inadequate provision for adaptation. {8.2, Table 8-2}

Climate change will have profound impacts on a broad spectrum of infrastructure systems (water and energy supply, sanitation and drainage, transport and telecommunication), services (including health care and emergency services), the built environment, and ecosystem services. These interact with other social, economic, and environmental stressors exacerbating and compounding risks to individual and household well-being (*medium confidence*, based on *medium evidence*, *high agreement*). {8.2}

Cities and city regions are sufficiently dense and of a spatial scale that they influence their local micro-climate. Climate change will interact with these conditions in a variety of ways, some of which will exacerbate the level of climate risk (*high confidence*, based on *robust evidence*, *high agreement*). {8.2}

Urban climate adaptation provides opportunities for both incremental and transformative development. {8.3, 8.4}

Urban adaptation provides opportunities for incremental and transformative adjustments to development trajectories toward resilience and sustainable development via effective multilevel urban risk governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector, and appropriate financing and institutional development. Opportunities to do so are high in many rapidly growing cities where institutions and infrastructure are being developed, though there is limited evidence of this being realized in practice (*medium confidence*, based on *limited evidence*, *high agreement*). {8.4}

Urban adaptation can enhance economic comparative advantage, reducing risks to enterprises and to households and communities (*medium confidence*, based on *medium evidence*, *high agreement*). {8.3}

City-based disaster risk management with a central focus on risk reduction is a strong foundation on which to address increasing exposure and vulnerability and thus to build adaptation. Closer integration of disaster risk management and climate change adaptation along with the incorporation of both into local, subnational, national, and international development policies can provide benefits at all scales (*high confidence*, based on *medium evidence*, *high agreement*). {8.3}

Ecosystem-based adaptation is a key contributor to urban resilience (*medium confidence*, based on *medium evidence*, *high agreement* (among practitioners)). {8. 3}

Effective urban food-security related adaptation measures (especially social safety nets but also including urban and peri-urban agriculture, local markets, and green roofs) can reduce climate vulnerability especially for low-income urban dwellers (*medium confidence*, based on *medium evidence*, *medium agreement*). {8.3}

Good quality, affordable, well-located housing provides a strong base for city-wide climate change adaptation minimizing current exposure and loss. Possibilities for building stock adaptation rest with owners and public, private, and civil society organizations (*high confidence*, based on *robust evidence*, *high agreement*). {8.3, 8.4}

Reducing basic service deficits and building resilient infrastructure systems (water supply, sanitation, storm and waste water drains, electricity, transport and telecommunications, health care, education, and emergency response) can significantly reduce hazard exposure and vulnerability to climate change, especially for those who are most at risk or vulnerable (*very high confidence*, based on *robust evidence*, *high agreement*). {8.3}

For most key climate change associated hazards in urban areas, risk levels increase from the present (with current adaptation) to the near term but high adaptation can reduce these risk levels significantly. It is less able to do so for the longer term, especially under a global mean temperature increase of 4°C. {Tables 8-3, 8-6}

Implementing effective urban adaptation is possible and can be accelerated. {8.4}

Urban governments are at the heart of successful urban climate adaptation because so much adaptation depends on local assessments and integrating adaptation into local investments, policies, and regulatory frameworks (*high confidence*). {8.4}

Well governed cities with universal provision of infrastructure and services have a strong base for building climate resilience if processes of planning, design, and allocation of human capital and material resources are responsive to emerging climate risks (*medium confidence*, based on *medium evidence*, *high agreement*). {8.4}

Building human and institutional capacity for adaptation in local governments, including scope for reflecting on incremental and transformative adaptation pathways, accelerates implementation and improves urban adaptation outcomes (*high confidence*, based on *medium evidence*, *high agreement*). {8.4}

Coordinated support from higher levels of governments, the private sector, and civil society and horizontal learning through networks of cities and practitioners benefits urban adaptation (*medium confidence*, based on *medium evidence*, *medium agreement*). {8.4}

Leadership within local governments and also across all scales is important in driving successful adaptation and in promoting and sustaining a broad base of support for the urban adaptation agenda (*medium confidence*, based on *medium evidence*, *high agreement*). {8.4}

Addressing political interests, mobilizing institutional support for climate adaptation, and ensuring voice and influence to those most at risk are important strategic adaptation concerns (*medium confidence*, based on *limited evidence*, *medium agreement*). {8.4}

Enabling the capacity of low-income groups and vulnerable communities, and their partnership with local governments, can be an effective urban adaptation strategy (*medium confidence*, based on *limited evidence*, *high agreement*). {8.3, 8.4}

Urban centers around the world face severe constraints to raising and allocating resources to implement adaptation. In most low- and middle-income country cities, infrastructure backlogs, lack of appropriate mandates, and lack of financial and human resources severely constrain adaptation action. Small urban centers often lack economies of scale for adaptation investments and local capacity to act, as they have relatively low national and international profiles (*medium confidence*, based on *medium evidence*, *high agreement*). {8.3, 8.4}

International financial institutions provide limited financial support for adaptation in urban areas. There is limited current commitment to finance urban adaptation from different levels of government and international agencies (*medium confidence*, based on *limited evidence*, *high agreement*). {8.4}

A scientific evidence base in each urban center is essential for effective adaptation action. This includes local risk and vulnerability assessments and information and data with which to consider current and future risk and adaptation and development options (*medium confidence*, based on *medium evidence*, *high agreement*). {8.4}

Dealing with the uncertainty associated with climate change projections and balancing them with actions to address current vulnerabilities and adaptation costs helps to assist implementation in urban areas (*medium confidence*, based on *medium evidence*, *medium agreement*). {8.2, 8.4}

8.1. Introduction

8.1.1. Key Issues

Adaptation to climate change depends centrally on what is done in urban centers, which now house more than half the world's population and concentrate most of its assets and economic activities (World Bank, 2008; UN DESA Population Division, 2012). As Section 8.4 emphasizes, this will require responses by all levels of government as well as individuals and communities, the private sector, and civil society. The serious impacts of extreme weather on many urban centers each year demonstrate some of the risks and vulnerabilities to be addressed (UNISDR, 2009; IFRC, 2010). Climate change will usually add to these and other risks and vulnerabilities. Urban policies also have major implications for mitigation, especially for future levels of greenhouse gas (GHG) emissions and for delivering co-benefits, as discussed in WGIII AR5. This chapter focuses on the possibilities for governments, enterprises, and populations to adapt urban centers to the direct and indirect impacts of climate change.

The level of funding needed for sound urban adaptation could exceed the capacities of local and national governments and international agencies (Parry et al., 2009; Brugmann, 2012). Much of the investment will have to come from individuals and households, communities, and firms through their decisions to address adaptation and resilience (Agrawala and Fankhauser, 2008; Fankhauser and Soare, 2013). This might suggest little role for governments, especially local governments. But whether these small-scale decisions by households, communities, and firms do contribute to adaptation depends in large part on what local governments do, encourage, support, and prevent—as well as their contribution to providing required infrastructure and services. An important part of this is the provision by local governments of appropriate regulatory frameworks and the application of building standards, to ensure that the choices made by individuals, households, and firms support adaptation and prevent maladaptation. For instance, land use planning and management have important roles in ensuring sufficient land for housing that avoids dangerous sites and protects key ecological services and systems (UN-HABITAT, 2011a).

In reviewing adaptation needs and options for urban areas, the documentation reviewed for this chapter points to two key conclusions. The first is how much the adaptive capacity of any city depends on the quality of provision and coverage of infrastructure and services; the capacities for investments and land use management; and the degree to which buildings and infrastructure meet health and safety standards. This capacity provides a foundation for city resilience on which adaptation can be built. There is little of this foundation in most urban centers in low-income and in many middle-income nations. The second conclusion is the importance of city and municipal governments acting now to incorporate climate change adaptation into their development plans and policies and infrastructure investments. This includes not only building that foundation of resilience (and its institutional, governance, and financial underpinnings) but also mobilizing new resources, adjusting building and land use regulations, and continuously developing the local capacity to respond. This is not to diminish the key roles of other actors. But it will fall to city and municipal government to provide the scaffolding and regulatory framework within which other stakeholders contribute and collaborate. Thus, adaptation in urban areas depends on the competence and capacity of local governments and a locally rooted iterative process of learning about changing risks and opportunities, identifying and evaluating options, making decisions, and revising strategies in collaboration with a range of actors.

8.1.2. Scope of the Chapter

This chapter focuses on what we know about the potential impact of climate change on urban centers and their populations and enterprises (Section 8.2), what measures are being taken to adapt to these changes (and protect vulnerable groups) (Section 8.3), and what institutional and governance changes can underpin adaptation (Section 8.4). Both this and Chapter 9 highlight the multiple linkages between rural and urban areas that have relevance for adaptation. This chapter also overlaps with Chapter 10, especially in regard to infrastructure, although this chapter focuses on urban infrastructure and in particular the infrastructure that comes within the responsibilities or jurisdiction of urban governments.

This chapter draws its urban statistics from the United Nations Population Division (UN DESA Population Division, 2012). Urban centers vary from those with a few thousand (or in some nations a few hundred) inhabitants to metropolitan areas with more than 20 million inhabitants. There is no international agreement—and considerable national variation—in how urban areas are defined (UN DESA Population Division, 2012). The main differences are in how settlements with a few hundred up to 20,000 inhabitants are classified; depending on the country, some, most, or all of these may be classified as urban or rural. There are also differences in how urban boundaries are set. In some places, they encompass the urban built up area or the central urban core; in others, they go well beyond the built up area and include large areas devoted to agriculture (Satterthwaite, 2007).

The issue here is whether provision for adaptation includes "rural" populations living around urban centers and within urban jurisdictions. In addition, it is common for part of the workforce in larger urban centers to live outside the urban center and to commute—and this may include many that live in settlements designated as rural. There is also no agreed definition for what constitutes a city—although the term city implies an urban center with some economic, political, or cultural importance and would not be applied to most small urban centers.

8.1.3. Context: An Urbanizing World

In 2008, for the first time, more than half the world's population was living in urban centers and the proportion continues to grow (UN DESA Population Division, 2012). Three-quarters of the world's urban population and most of its largest cities are now in low- and middle-income nations. A comparison of Figures 8-1 and 8-2 highlights the increase in the number of large cities from 1950 to what is projected for 2025. UN projections suggest that almost all the increase in the world's population up to 2050 will be in urban centers in what are currently low- and middle-income nations (see Table 8-1). Most of the gross domestic product (GDP) of most nations and globally is generated in urban centers and most new investments have concentrated there (World Bank, 2008; Satterthwaite et al., 2010). Clearly, just in terms of the population, economic activities, assets, and climate risk they increasingly concentrate, adapting urban areas to climate change requires serious attention.

Most urbanization is underpinned by an economic logic. All wealthy nations are predominantly urbanized and rapid urbanization in low- and middle-income nations is usually associated with rapid economic growth (World Bank, 2008; Satterthwaite et al., 2010). Most of the world's largest cities are in its largest economies (World Bank, 2008;

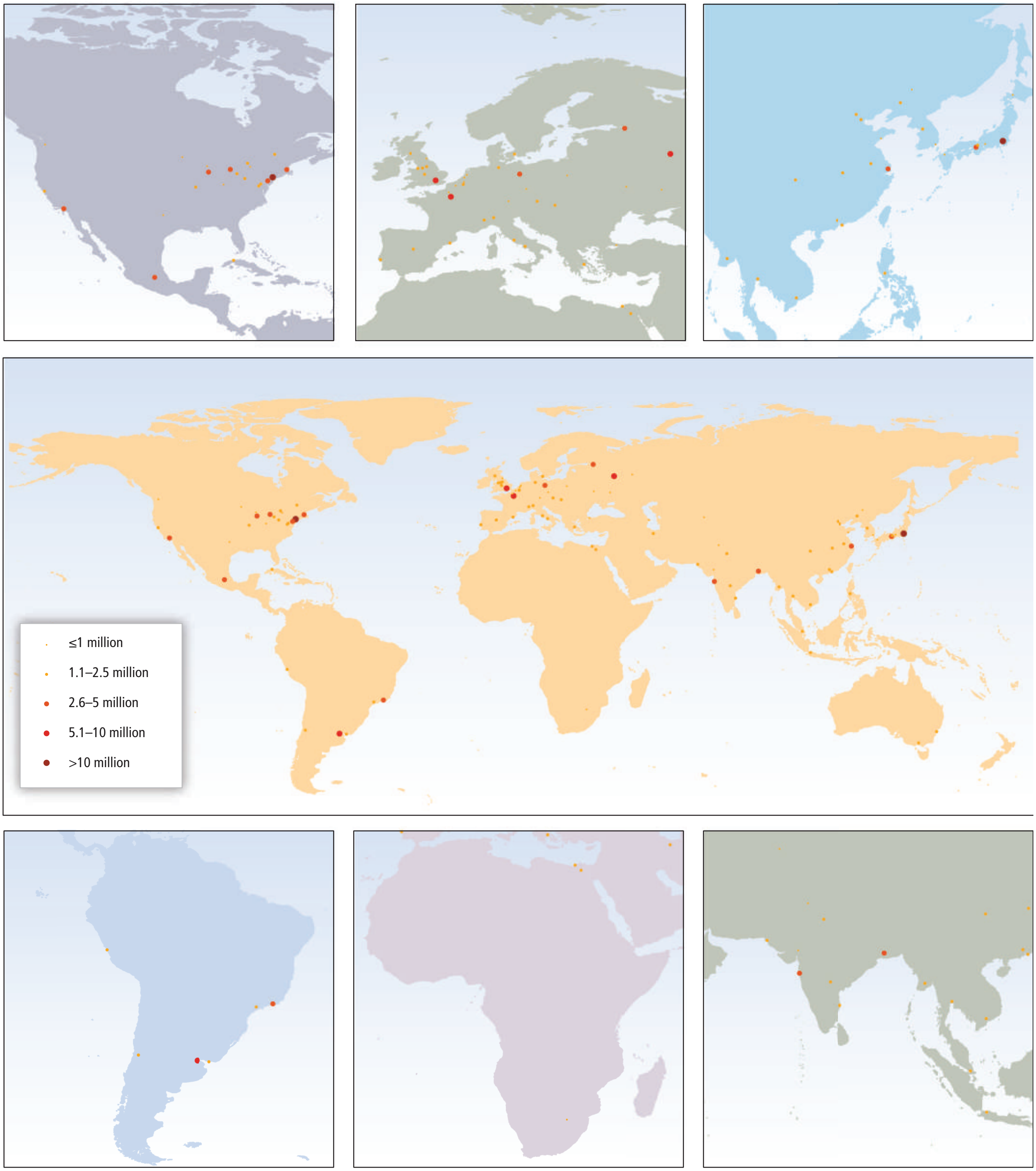


Figure 8-1 | Global and regional maps showing the location of urban agglomerations with 750,000-plus inhabitants in 1950 (derived from statistics in UN DESA Population Division, 2012).

Satterthwaite et al., 2010). If rapid urbanization and rapid city population growth are associated with economic success, it suggests that more resources should be available there to support adaptation. But, as discussed in Section 8.3, this is rarely the case. In most urban centers in low- and middle-income nations including many successful cities, local governments have been unable to manage their economic and physical expansion and there are large deficits in provision for infrastructure and services that are relevant to climate change adaptation. About one in seven people in the world live in poor quality, overcrowded accommodation in urban areas with inadequate provision (or none) for basic infrastructure

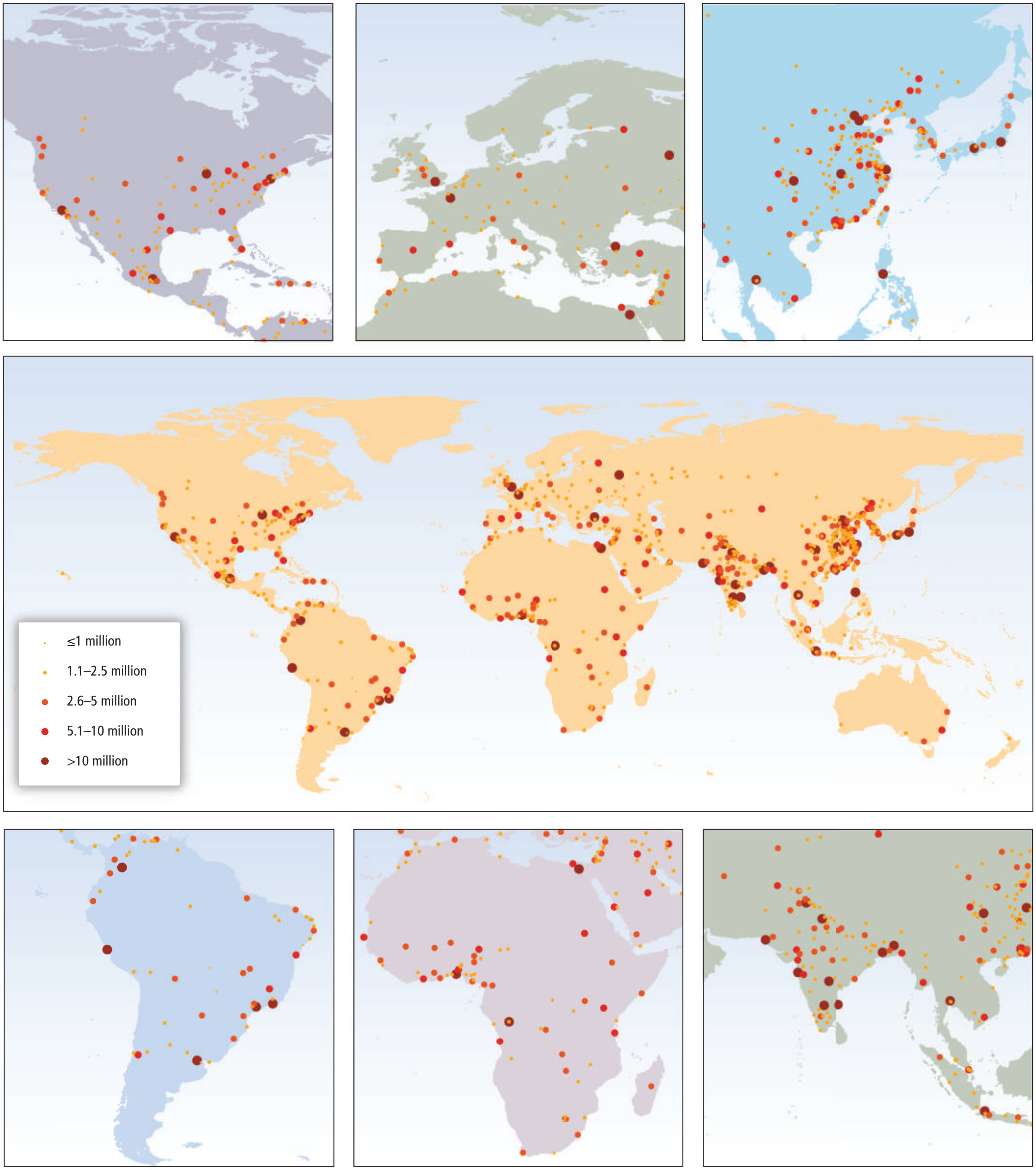


Figure 8-2 | Global and regional maps showing the location of urban agglomerations with 750,000-plus inhabitants projected for 2025 (derived from statistics in UN DESA Population Division, 2012).

8

Table 8-1 | Distribution of the world's urban population by region, 1950–2010 with projections to 2030 and 2050. Source: Derived from statistics in United Nations (2012).

	Major area, region, or country	1950	1970	1990	2010	Projected for 2030	Projected for 2050
Urban population (millions of inhabitants)	**World**	745	1352	2281	3559	4984	6252
	More developed regions	442	671	827	957	1064	1127
	Less developed regions	304	682	1454	2601	3920	5125
	Least developed countries	15	41	107	234	477	860
	Sub-Saharan Africa	20	56	139	298	596	1069
	Northern Africa	13	31	64	102	149	196
	Asia	245	506	1032	1848	2703	3310
	China	65	142	303	660	958	1002
	India	63	109	223	379	606	875
	Europe	281	412	503	537	573	591
	Latin America and the Caribbean[a]	69	163	312	465	585	650
	Northern America	110	171	212	282	344	396
	Oceania	8	14	19	26	34	40
Percent of the population in urban areas	**World**	29.4	36.6	43.0	51.6	59.9	67.2
	More developed regions	54.5	66.6	72.3	77.5	82.1	85.9
	Less developed regions	17.6	25.3	34.9	46.0	55.8	64.1
	Least developed countries	7.4	13.0	21.0	28.1	38.0	49.8
	Sub-Saharan Africa	11.2	19.5	28.2	36.3	45.7	56.5
	Northern Africa	25.8	37.2	45.6	51.2	57.5	65.3
	Asia	17.5	23.7	32.3	44.4	55.5	64.4
	China	11.8	17.4	26.4	49.2	68.7	77.3
	India	17.0	19.8	25.5	30.9	39.8	51.7
	Europe	51.3	62.8	69.8	72.7	77.4	82.2
	Latin America and the Caribbean	41.4	57.1	70.3	78.8	83.4	86.6
	Northern America	63.9	73.8	75.4	82.0	85.8	88.6
	Oceania	62.4	71.2	70.7	70.7	71.4	73.0
Percent of the world's urban population	**World**	100.0	100.0	100.0	100.0	100.0	100.0
	More developed regions	59.3	49.6	36.3	26.9	21.4	18.0
	Less developed regions	40.7	50.4	63.7	73.1	78.6	82.0
	Least developed countries	2.0	3.0	4.7	6.6	9.6	13.8
	Sub-Saharan Africa	2.7	4.1	6.1	8.4	11.9	17.1
	Northern Africa	1.7	2.3	2.8	2.9	3.0	3.1
	Asia	32.9	37.4	45.2	51.9	54.2	52.9
	China	8.7	10.5	13.3	18.6	19.2	16.0
	India	8.5	8.1	9.8	10.6	12.2	14.0
	Europe	37.6	30.5	22.0	15.1	11.5	9.5
	Latin America and the Caribbean	9.3	12.1	13.7	13.1	11.7	10.4
	Northern America	14.7	12.6	9.3	7.9	6.9	6.3
	Oceania	1.1	1.0	0.8	0.7	0.7	0.6

[a]Chapter 26 on North America includes Mexico; in the above statistics, Mexico is included in Latin America and the Caribbean.

and services, mostly in informal settlements (UN-HABITAT, 2003a; Mitlin and Satterthwaite, 2013). Much of the health risk and vulnerability to climate change is concentrated in these settlements (Mitlin and Satterthwaite, 2013). So this chapter is concerned not only with an adaptation deficit for, but also with a development deficit that is relevant to, this risk and vulnerability.

Many aspects of urban change in recent decades have been so rapid that they have overwhelmed government capacity to manage them. Among the 611 cities with more than 750,000 inhabitants in 2010, 47 had populations that had grown more than 20-fold since 1960; in 120, the growth was more than 10-fold (statistics in this paragraph are drawn from data in UN DESA Population Division, 2012). The increasing concentration of the world's urban population and its largest cities outside the highest income nations represents an important change. Over the 19th and 20th centuries, most of the world's urban population and most of its largest cities were in its most prosperous nations. Now, urban areas in low- and middle-income nations have close to two-fifths of the world's total population, close to three-quarters of its urban population, and most of its large cities. In 2011, of the 23 "mega-cities" (with populations over 10 million), only 5 were in high-income nations (two in Japan, two in the USA, one in France). Of the remaining 18, 4 were in China, 3 in India, and 2 in Brazil. But more than three-fifths of the world's urban population is in urban centers with fewer than 1 million inhabitants and it is here that much of the growth in urban population is occurring.

Underlying these population statistics are large and complex economic, social, political, and demographic changes, including the multiplication in the size of the world's economy and the shift in economic activities and employment structures from agriculture to industry and services (and within services to information production and exchange) (Satterthwaite, 2007). One of the most significant changes has been the growth in the size and importance of cities whose economies increased and changed as a result of globalization (Sassen, 2012). Another is the number of large cities that are now centers of large extended metropolitan regions.

One of the challenges for this chapter is to convey the very large differences in adaptive capacity between urban centers. There are tens of thousands of urban centers worldwide with very large and measurable differences in population, area, economic output, human development, quality, and coverage of infrastructure and services, ecological footprint, and GHG emissions. The differences in adaptive capacity are far less easy to quantify. Table 8-2 illustrates differences in adaptive capacity and factors that influence it. It indicates how each urban center falls within a spectrum in at least four key factors that influence adaptation: local government capacity; the proportion of residents served with risk-reducing infrastructure and services; the proportion living in housing built to appropriate health and safety standards; and the levels of risk from climate change's direct and indirect impacts. This chapter and Table 8-2 also draw on detailed case studies to illustrate this diversity—New York (Solecki, 2012), Durban (Roberts and O'Donoghue, 2013), and Dar es Salaam (Kiunsi, 2013). Section 8.5 provides tables of current and indicative future climate risks for Dar es Salaam, Durban, London, and New York.

Many attributes of urban centers can be measured and compared. As noted above, populations vary from a few hundred to more than 20 million. Areas vary from less than one to thousands of square kilometers. Average life expectancy at birth varies from more than 80 years to less than 40 years, and under-five mortality rates vary by a factor of 20 or more (Mitlin and Satterthwaite, 2013). Average per capita incomes vary by a factor of at least 300; so too does the funding available to local governments per person (UCLG, 2010). GHG emissions per person (in tonnes of carbon dioxide equivalent) vary by more than 100 (Dodman, 2009; Hoornweg et al., 2011).

There are large differences between urban centers in the extent to which their economies are dependent on climate-sensitive resources (including commercial agriculture, water, and tourism).There are also large variations in the scale and nature of impacts from extreme weather. As Table 8-2 suggests, there are urban indicators relevant for assessing the resilience to climate change impacts that urban areas have acquired (including the proportion of the population with water piped to their homes, sewers, drains, health care, and emergency services); it is more of a challenge to find indicators for the climate change related risks and for the quality and capacity of government.

Recent analyses of disaster impacts show that a high proportion of the world's population most affected by extreme weather events is concentrated in urban centers (UNISDR, 2009, 2011; IFRC, 2010). As shown in Table 8-2, a high proportion of these urban centers lack both local governments with the capacity to reduce disaster risk, and much of the necessary infrastructure. Their low-income households may require particular assistance because of greater exposure to hazards, lower adaptive capacity, more limited access to infrastructure or insurance, and fewer possibilities to relocate to safer accommodation, compared to wealthier residents.

All successful urban centers have had to adapt to environmental conditions and available resources, although local resource constraints have often been overcome by drawing on resources and using sinks from "distant elsewhere" (Rees, 1992; McGranahan, 2007); this includes importing goods that are resource intensive and whose fabrication involves large GHG emissions. The growth of urban population over the last century has also caused a very large anthropogenic transformation of terrestrial biomes. Urban centers cover only a small proportion of the world's land surface—according to Schneider et al. (2009) only 0.51% of the total land area; only in Western Europe do they cover more than 1%. However, their physical and ecological footprints are much larger. The net ecological impact of urban centers includes the decline in the share of wild and semi-natural areas from about 70% to less than 50% of land area, largely to accommodate crop and pastoral land to support human consumption (Ellis et al., 2010). It has led not only to a decrease in biodiversity but to fragmentation in much of the remaining natural areas and a threat to the ecological services that support both rural and urban areas. Future projections (Seto et al., 2012) suggest that, if current trends continue, urban land cover will increase by 1.2 million km^2 by 2030, nearly tripling global urban land area between 2000 and 2030. This would mean a "considerable loss of habitats in key biodiversity hotspots," destroying the green infrastructure that is key in helping areas adapt to climate change impacts (Seto et al., 2012, p. 16083) as well as increasing the exposure of population and assets to higher risk levels.

Many of the challenges and opportunities for urban adaptation relate to the central features of city life—the concentration of people, buildings, economic activities, and social and cultural institutions (Romero-Lankao and Dodman, 2011). Agglomeration economies are usually discussed in relation to the advantages for enterprises locating in a particular city. But the concentrations of people, enterprises, and institutions in urban areas also provide potential agglomeration economies in lower unit costs for piped water, sewers, drains, and a range of services (solid waste collection, schools, health care, emergency services, policing) and in the greater capacity for people, communities, and institutions to respond collectively (Hardoy et al., 2001). At the same time, the advantages that come with these concentrations of people and activities are also accompanied by particular challenges—for instance, the management of storm and surface runoff and measures to reduce heat islands. Large cities concentrate demand and the need for ecological services and natural resources (water, food, and biomass), energy, and electricity, and many city enterprises rely on lifeline infrastructure and supply chains that can be disrupted by climate change (UNISDR, 2013; see also Section 8.3.3).

Table 8-2 | The large spectrum in the capacity of urban centers to adapt to climate change. One of the challenges for this chapter is to convey the very large differences in adaptive capacity between urban centers. This table seeks to illustrate differences in adaptive capacity and the factors that influence it. For a more detailed assessment of adaptation potentials and challenges for specific cities (Dar es Salaam, Durban, London, and New York), see Table 8-6. Sources: This table was constructed to provide a synthesis of key issues, so it draws on all the sources cited in this chapter. However, it draws in particular on Solecki (2012), Kiunsi (2013), and Roberts and O'Donoghue (2013).

Indicator clusters	Very little adaptive capacity or resilience/ "bounce-back" capacity	Some adaptive capacity and resilience/"bounce-back" capacity	Adequate capacity for adaptation and resilience/"bounce-back" capacity, but not yet acted on	Climate resilience and capacity to bounce forward	Transformative adaptation
The proportion of the population served with risk-reducing infrastructure (paved roads, storm and surface drainage, piped water…) and services relevant to resilience (including health care, emergency services, policing/rule of law) and the institutions needed for such provision	0–30% of the urban center's population served; most of those unserved or inadequately served living in informal settlements.	30–80% of the urban center's population served; most of those unserved or inadequately served living in informal settlements.	80–100% of the urban center's population served; most of those unserved or inadequately served living in informal settlements.	Most/all of the urban center's population with these and with an active adaptation policy identifying current and probable future risks and with an institutional structure to encourage and support action by all sectors and agencies. In many cities, also upgrade aging infrastructure.	Urban centers that have integrated their development and adaptation policies and investments within an understanding of the need for mitigation and sustainable ecological footprints.
The proportion of the population living in legal housing built with permanent materials (meeting health and safety standards)				Active program to improve conditions, infrastructure, and services to informal settlements and low-income areas. Identify and act on areas with higher/ increasing risks. Revise building standards.	Land use planning and management successfully providing safe land for housing, avoiding areas at risk and taking account of mitigation.
Proportion of urban centers covered	Most urban centers in low-income and many in middle-income nations.	Many urban centers in many low-income nations; most urban centers in most middle-income nations.	Virtually all urban centers in high-income nations, many in middle-income nations.	A small proportion of cities in high-income and upper-middle-income nations.	Some innovative city governments thinking of this and taking some initial steps.
Estimated number of people living in such urban centers	1 billion	1.5 billion	1 billion	Very small	
Infrastructure deficit	Much of the built up area lacking infrastructure				Most or all the built up area with infrastructure (paved roads, covered drains, piped water…)
Local government investment capacity	Very little or no local investment capacity				Substantial local investment capacity
Occurrence of disasters from extreme weather[a]	Very common				Uncommon (mostly due to risk-reducing infrastructure, services, and good quality buildings available to almost all the population)
Examples	Dar es Salaam, Dhaka	Nairobi, Mumbai	Most cities in high-income nations	Cities such as New York; London, Durban, and Manizales with some progress	
Implications for climate change adaptation	Very limited capacity to adapt. Very large deficits in infrastructure and in institutional capacity. Very large numbers exposed to risk if these are also in locations with high levels of risk from climate change.	Some capacity to adapt, especially if this can be combined with development, but difficult to get city governments to act. Particular problems for those urban centers in locations with high levels of risk from climate change.	Strong basis for adaptation, but needs to be acted on and to influence city government and many of its sectoral agencies.	City government that is managing land use changes as well as having adaptation integrated into all sectors.	City government with capacity to influence and work with neighboring local government units. Also with land use changes managed to protect eco-system services and support mitigation.

Notes: For cities that are made up of different local government areas, it would be possible to apply the above at an intra-city or intra-metropolitan scale. For instance, for many large Latin American, Asian and African cities, there are local government areas that would fit in each of the first three categories.

[a]See text in regard to disasters and extensive risk (United Nations, 2011).

The increasing concentration of the world's population in urban centers means greater opportunities for adaptation but more concentrated risk if they are not acted on. Many urban governments lack the capacity to do so, especially those in low- and lower-middle-income nations. The result is large deficiencies in infrastructure and services. Urban centers in high-income nations, although much better served, may also face particular challenges—for instance, aging infrastructure and the need to adapt energy systems, building stock, infrastructure, and services to the altered risk set that climate change will bring (see Zimmerman and Faris (2010) and Solecki (2012) for discussions of this for New York). Many studies have shown that working with a range of government and civil society institutions at local and supra-local levels increases the effectiveness of urban adaptation efforts; support and enabling frameworks from higher levels of government were also found to be helpful (see Section 8.4 and many of the studies listed in Box 8-1).

8.1.4. Vulnerability and Resilience

For each of the direct and indirect impacts of climate change, there are groups of urban dwellers that face higher risks (illness, injury, mortality, damage to or loss of homes and assets, disruption to incomes) (Hardoy and Pandiella, 2009; Mitlin and Satterthwaite, 2013). Age may be a factor (for instance infants and elderly people are more sensitive to particular hazards such as heat stress) or health status (those with particular diseases, injuries, or disabilities may be more sensitive to these impacts). Or it may be that they live in buildings or in locations facing greater risks—for instance on coasts or by rivers with increased flood risks—or that they lack coping capacities. Women may face higher risks in their work and constraints on adaptation if they face discrimination in access to labor markets, resources, finance, services, and influence (see Box CC-GC). These are often termed vulnerable groups—although, to state the obvious, they are vulnerable to direct climate change impacts only to the extent that the hazard actually poses a risk. Remove people's exposure to the hazard (e.g., provide drains that prevent flooding) and there is limited or no impact. Infants may face serious health risks when water supplies are contaminated by flooding, but rapid and effective treatment for diarrhea and quickly re-establishing availability of drinking quality water greatly reduces impacts (Bartlett, 2008). Adaptations by individuals, households, communities, private enterprises, or government service providers can all reduce risks.

Adaptation in a particular area or settlement may have clear benefits for the inhabitants there, but can also have knock-on effects on the well-being of inhabitants in other areas. Diverting a river course or building an embankment to protect new development may prevent flooding in one location, but may cause or increase flooding somewhere else (see Revi, 2005, for Mumbai; Alam and Rabbani, 2007, for Dhaka).

Assessments of vulnerability to climate change draws on assessments in other contexts—including the vulnerability of low-income groups to stresses and shocks (e.g., Chambers, 1989; Pryer, 2003) and to disasters (Cannon, 1994; Manyena, 2006). The term is generally used in relation to an inability to cope with external changes including avoiding harm when exposed to a hazard. This includes people's inability to avoid the hazard (exposure), anticipate it, and take measures to avoid it or limit its impact; cope with it; and recover from it (Hardoy and Pandiella, 2009). Vulnerable groups may be identified on the basis of any of these four factors. The definition of resilience used in the WGII AR5 when applied to urban centers means the ability of urban centers (and their populations, enterprises, and governments) and the systems on which they depend to anticipate, reduce, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner (see the Glossary).

The term vulnerability is also applied to sectors, including food processing, tourism, water, energy, and mobility infrastructure and their cross-linkages, for instance, the dependency of perishable commodities on efficient transport. Much tourism is sensitive to climate change, which can damage key tourist assets such as coral reefs and beaches or make particular locations less attractive to tourists because of more extreme weather. The term is also applied to natural systems/ecosystems (e.g., mangroves, coastal wetlands, urban tree canopy). If the adaptive capacity of these systems is increased, they can also provide natural protection from the impacts of climate change in urban areas (see, e.g., Sections 8.2.4.5, 8.3.3.7 for more details).

8.1.4.1. Differentials in Risk and Vulnerability within and between Urban Centers

In urban centers where virtually all buildings meet health and safety standards, where land use planning prevents developments on sites at risk, and where there is universal provision for infrastructure and basic services, the exposure differentials between high- and low-income groups to climate-related risk are quite low. Having low income and few assets in such urban centers does not necessarily imply greater vulnerability to climate change (Mitlin and Satterthwaite, 2013). But typically, the larger the deficit in infrastructure and service provision, the larger the differentials in exposure to most climate change impacts between income groups. Low-income groups in low- and middle-income nations are often disproportionately vulnerable because of poor quality and insecure housing; inadequate infrastructure; and lack of provision for health care, emergency services, and disaster risk reduction (UNISDR, 2009; IFRC, 2010; UN-HABITAT, 2011a; IPCC, 2012; Mitlin and Satterthwaite, 2013). Most deaths from disasters are concentrated in low- and middle-income countries—including more than 95% of deaths from natural disasters between 1970 and 2008 (IPCC, 2012). More than 95% of the deaths from storms and floods registered on the EM-DAT from 2000 to September 2013 were in low- and middle-income nations.[1]

An analysis of annual fatalities from tropical cyclones showed these to be heavily concentrated in low-income nations even though there was high exposure in many upper-middle- and high-income nations (and these nations had larger economic losses; UNISDR, 2009). These analyses do not separate rural and urban populations—but there is a growing body of evidence that most urban deaths from extreme weather events are in low-income and lower-middle-income countries (UNISDR, 2009; IFRC, 2010). Analyses of risks across many cities usually show the cities at highest risk from extreme weather or particular kinds of such weather

1 These are drawn from data in the The International Disaster Database EM-DAT accessed on September 16, 2013.

(e.g., floods) to be primarily in high-income countries (Munich Re, 2004; Hallegatte et al., 2013). But this is because these analyses are based on estimates of economic costs or economic losses. If they were based instead on deaths and injuries, the ranking would change fundamentally (see also Balica et al., 2012). The official statistics on disaster deaths are also known to considerably understate total deaths, in part because many deaths go unrecorded, in part because of the criteria that a disaster event has to meet to be included (one of the following criteria must be fulfilled: ten or more people reported killed; 100 or more people reported affected; declaration of a state of emergency; or call for international assistance) (UNISDR, 2009).

There are dramatic examples of extreme weather events in high-income countries with very large impacts, including high mortality. But the analyses in UNISDR (2009) and IFRC (2010), and the reports of deaths from extreme weather in many of the case studies listed in Box 8-1, suggest that most extreme weather disaster deaths in urban centers are in low- and lower-middle-income nations, and that risks are concentrated in informal settlements. As noted by IPCC (2012), the occupants of these settlements are typically more exposed to climate events with limited or no hazard-reducing infrastructure, low-quality housing, and limited capacity to cope.

Where provision for adequate housing, infrastructure, and services is most lacking, the capacity of individuals, households, and community organizations to anticipate, cope, and recover from the direct and indirect losses and impact of disasters (of which climate-related events are a subset) becomes increasingly important (see Section 8.4). The effectiveness of early warning systems, the speed of response, and the effectiveness of post-disaster response is especially important to those who are more sensitive and have less coping capacity. The effectiveness of such responses depends on an understanding of the specific vulnerabilities, needs, and priorities of different income groups, age groups, and groups that face discrimination, including that faced by women and by particular social or ethnic groups (UN-HABITAT, 2011a).

8.1.4.2. Understanding Resilience for Urban Centers in Relation to Climate Change

In relation to disasters, resilience is usually considered to be the opposite of vulnerability, but vulnerability is often discussed in relation to particular population groups while resilience is more often discussed in relation to the systemic capacity to protect them and reduce the impact of particular hazards through infrastructure or climate-risk sensitive land use management. In recent years, a literature has emerged discussing resilience to climate change for urban centers and what contributes to it (Muller, 2007; Leichenko, 2011; Moench et al., 2011; Pelling, 2011a; Brown et al., 2012; da Silva et al., 2012). Addressing resilience for cities is more than identifying and acting on specific climate change impacts. It looks at the performance of each city's complex and interconnected infrastructure and institutional systems including interdependence between multiple sectors, levels, and risks in a dynamic physical, economic, institutional, and socio-political environment (Kirshen et al., 2008; Gasper et al., 2011). When resilience is considered for cities, certain systemic characteristics are highlighted—for instance flexibility, redundancy, responsiveness, capacity to learn, and safe failure (Tyler et al., 2010; Moench et al., 2011; Brown et al., 2012; da Silva et al., 2012), as well as take account of the multiple interdependencies between different sectors (see Section 8.2).

When a specific city is being considered, the level and forms of resilience are often related to specific local factors, services, and institutions—for instance, for each district in a city, will the storm and surface drains cope with the next heavy rainfall? During hot days, will measures to help those at risk from heat stress reach all high-risk groups (see Box CC-HS for more detail)? Here, resilience is not only the ability to recover from the impact but also the ability to avoid or minimize the need to recover and the capacity to withstand unexpected or unpredicted changes (UNISDR, 2011). An important aspect of resilience is the functioning of institutions to make this possible and the necessary knowledge base (da Silva et al., 2012).The emerging literature on the resilience of cities to climate change also highlights the need to focus on resource availabilities and sinks beyond the urban boundaries. It may also require coordinated actions by institutions in other jurisdictions or higher levels of government, for example, watershed management upstream of a city to reduce flood risks (Ramachandraiah, 2011; Brown et al., 2012). There are also the slow onset impacts that pose particular challenges and that may also be outside the jurisdiction of urban governments—for instance, the impact of drought on agriculture, which can raise food prices and reduce rural incomes and demand for urban services.

Resilience to extreme weather for urban dwellers is strongly influenced by factors already mentioned—the quality of buildings, the effectiveness of land use planning, and the quality and coverage of key infrastructure and services. It is also influenced by the effectiveness of early warning systems and public response measures (IFRC, 2010; UN-HABITAT, 2011a) and by the proportion of households with savings and insurance and able to afford safe, healthy homes. Safety nets for those with insufficient incomes are also important, along with the administrative capacity to ensure these reach those in need. Urban governments have importance for most of this, although their capacity to provide usually depends on the revenue raising powers and legislative and financial support from higher levels of government. These in turn are driven in part by political pressure from urban dwellers and innovation by city governments. Private companies or non-profit institutions may provide some of these but the framework for provision and quality control is provided by local government or local offices or national or provincial government.

Cities in high-income nations and many in middle-income nations have become more resilient to extreme weather (and other possible catalysts for disasters) through a range of measures responding to risks and to the political processes that demand such responses (IFRC, 2010; UN-HABITAT, 2011a; Satterthwaite, 2013). The universal provision of piped water, sewers, drains, health care and emergency services, and standards set and enforced on housing quality and infrastructure were not a response to climate change but what was built over the last 100 to 150 years in response to the needs and demands of residents. This has produced what can be termed accumulated resilience in the built environment to extreme weather and built the capacity of local governments to act on risk reduction (e.g., Hardoy and Ruete, 2013, on Rosario, Argentina). In addition, it helped build the institutions, finances, and governance systems that can support climate change adaptation (Satterthwaite, 2013). Building and infrastructure standards can be adjusted as required (if there is infrastructure in place that can be adjusted, e.g., by increasing capacity for storm and surface water drainage systems). Existing levels of service provision can be modified to take into account new risks or risk levels, as can city planning and land use management (e.g., by keeping city expansion away from areas facing higher risk levels). Private sector investments can support these kinds of adjustments (e.g., changing insurance premiums and coverage) (IFRC, 2010; UN-HABITAT, 2011a; UNISDR, 2013). All of these provide the foundation on which to build adaptive capacity to withstand climate change-related direct and indirect impacts.

Whether this will happen depends on willingness of urban governments to take this on, the demands of local inhabitants and their capacity to organize and press for change, and the capacity for learning and cooperation within local institutions. Obviously, it also depends on global agreements that slow and stop the increases in risk from GHG emissions and other drivers of climate change. Many cities with accumulated resilience may still not be equipped to respond to the changed hazards and risks associated with climate change (IPCC, 2012). The issue here becomes whether the institutions and political pressures that built the accumulated resilience are able to shift to resilience building as a directed process—and to respond dynamically and effectively to evolving and changing climate-related risks (and the evolving and changing knowledge bases that supports this).

For urban centers with little accumulated resilience, resilience as a process is also important, both to help reduce over time the (often very large) deficiencies in most or all the infrastructure, services, and regulatory frameworks that provide resilience in high-income nations and to build resilience to climate change impacts (see Table 8-2). For around a third of the world's urban population, this has to be done in a context of limited incomes and assets and poor living conditions and little current coping capacity to stresses or shocks (UNISDR, 2009; IPCC, 2012). Just an increase in the price of food staples, a drop in income, or a new cost, such as medicine for a sick family member, can quickly mean inadequate food, hunger, and reduced capacity to work (Mitlin and Satterthwaite, 2013).

This implies the need for a specific perspective on how climate change adaptation must be supported. It highlights the intimate relationship between resilience to climate change impacts and the quality of governance, especially local governance. The government's capacity and willingness to listen to, work with, support, and serve those who lack resilience is fundamental (IPCC, 2012). This is demonstrated by the many successful partnerships between local government and grassroots organizations formed by residents of informal settlements that have built or improved homes and neighborhoods (see Section 8.4).

Thus, resilience can be considered in relation to individuals/households, communities, and urban centers. In each of these, it includes the capacity to undertake anticipatory adaptation—action that avoids or reduces a climate change impact, for instance, by living in a safe location, having a safe house, or having risk-reducing infrastructure. It also includes reactive adaptation to cope with the impact of an event, to "bounce back" to the previous state (Shaw and Theobald, 2011). For urban centers, "bouncing back" includes the government capacity to rapidly restore key services and repair infrastructure. Ideally, for climate change adaptation, responses by urban populations, enterprises, and governments should allow "bounce forward" to a more resilient state. This is discussed in disaster risk reduction and is termed "building-back better" (Lyons, 2009). This is part of the shift from resilience to transformative adaptation shown in Table 8-2 where urban centers have integrated their development, disaster risk reduction, and adaptation policies and investments within an understanding of the need for mitigation and sustainable ecological footprints (see also Pelling and Dill, 2010; Manyena et al., 2011; Shaw and Theobald, 2011).

8.1.5. Conclusions from the Fourth Assessment Report (AR4) and New Issues Raised by this Chapter

AR4's chapter on Industries, Settlements, and Human Society (Wilbanks et al., 2007) notes that variability in environmental conditions has always been a given, but that when change is more extreme, persistent, or rapid than has been experienced in the past, especially if it is not foreseen and capacities for adaptation are limited, the risks will increase (WGII AR4 Section 7.1.1). The chapter also noted that, except for abrupt extreme events, climate change impacts are not currently dominant issues for urban centers (WGII AR4 Section 7.1.3). Their importance lies in their interaction with other stressors, which may include rapid population growth, political instability, poverty and inequality, ineffective local governments, jurisdictional fragmentation, and aging or inadequate infrastructure (WGII AR4 Section 7.2). Key challenges identified for turning attention to adaptation include the difficulties of estimating and projecting the magnitudes of climate risk in particular places and sectors with precision and a weak knowledge base on the costs of adaptation (issues that are still challenges today).

Wilbanks et al. (2007) describe how the interactions between urbanization and climate change have led to concentrations of urban populations in low-income nations with weak adaptive capacity. They also describe the interactions between climate change and a globalized economy with long supply chains, resulting in impacts spreading from directly affected areas and sectors to other areas and sectors through complex linkages (WGII AR4 Section 7.2). Many impacts will be unanticipated and overall effects are poorly estimated when only direct impacts are considered. Key global vulnerabilities include interregional trade and migration patterns. This chapter also describes how climate change impacts and most vulnerabilities are influenced by local contexts, including geographic location, the climate sensitivity of enterprises located there, development pathways, and population groups unable to avoid dangerous sites and homes (WGII AR4 Sections 7.3, 7.4.3). Key risks are most often related to climate phenomena that exceed thresholds for adaptation (e.g., extreme weather or abrupt changes) and limited resources or institutional capacities to reduce risk and cope (e.g., with increased demands on water and energy supplies and often on health care and emergency response systems).

Individual adaptation may not produce systemic adaptation. In addition, adaptation of systems may not benefit all individuals or households, because of the different vulnerability of particular groups and places (WGII AR4 Section 7.6.6). Adaptation will be well served by a greater awareness of threats and alternatives beyond historical experience and current access to finance. Technological innovation for climate adaptation comes largely from industry and services that are motivated by market signals, which may not be well matched with adaptation needs and residual uncertainties. Many are incremental adjustments to current business activities.

For the types of infrastructure most at risk—including most transport, drainage, and electricity transmission systems and many water supply abstraction and treatment works—reserve margins can be increased and back-up capacity developed (WGII AR4 Section 7.6.4). Adaptation of infrastructure and building stock often depends on changes in the institutions and governance framework, for example, in planning regulations and building codes. Climate change has become one of many changes to be understood and planned for by local managers and decision makers (WGII AR4 Section 7.6.7). For instance, planning guidance and risk management by insurers will have roles in locational choice for industry.

Since AR4, a much larger and more diverse literature has accrued on current and potential climate change risks for urban populations and centers (see Section 8.2). The literature on urban "adaptation" and on building resilience at city and regional scales has also expanded (see Sections 8.3, 8.4) including work on urban centers in low- and middle-income nations (see Box 8-1). Far more city governments have published documents on adaptation. There is more engagement with urban adaptation by some professions, including architects, engineers, urban planners, and disaster risk reduction specialists (Engineers Canada, 2008; UNISDR, 2009; Engineering the Future, 2011; UN-HABITAT, 2011a; da Silva, 2012). There are also assessments and books that focus specifically in climate change and cities with a strong focus on adaptation (Bicknell et al., 2009; Rosenzweig et al., 2011; UN-HABITAT, 2011a; Cartwright et al., 2012; Willems et al., 2012; Bulkeley, 2013).

This makes a concise and comprehensive summary more difficult. But it has also allowed for more clarity on what contributes to resilience in urban centers and systems. Specifically, there is now:

- A more detailed understanding of key urban climate processes, including drivers of climate change, and improved analytical and down-scaled integrated assessment models at regional and city scale
- A more detailed understanding on the governance of adaptation in urban centers and the adaptation responses being considered or taken; this includes a large and important gray literature produced by or for city governments and some international agencies and, in many high-income and some middle-income nations, support for this from higher levels of government
- More nuanced understanding of the many ways in which poverty and discrimination exacerbates vulnerability to climate impacts (see also Chapter 13)
- More detailed studies on particular built environment responses to promote adaptation (see, e.g., the growth in the literature on green and white roofs)
- More case studies of community-based adaptation and its potential contributions and limitations
- More consideration of the role of ecosystem services and of green (land) and blue (water) infrastructure in adaptation
- More consideration of the financing, enabling, and supporting of adaptation for households and enterprises
- More on learning from innovation in disaster risk reduction
- A greater appreciation of the interdependencies between different infrastructure networks and of the importance of "hard" infrastructure and of the institutions that plan and manage it
- More examples of city governments and their networks contributing to national and global discussions of climate change adaptation (and mitigation), including establishing voluntary commitments (see, e.g., the Durban Adaptation Charter for local governments) and engaging with the Conference of Parties.

A range of key uncertainties and research priorities emerge from the literature reviewed in this chapter:

- The limits to understanding and predicting impacts of climate change at a fine-grained geographic and sectoral scale
- Inadequate knowledge on the vulnerabilities of urban citizens and enterprises to the direct impacts of climate change, to second- and third-order impacts, and to the interdependence between systems
- Inadequate knowledge on the vulnerability of the built environment, buildings, building components, building materials, and the construction industry to the direct and indirect impacts of climate change and of the most effective responses for new-build and for retrofitting
- Inadequate knowledge on the adaptation potentials for each urban center (and its government) and their costs, and on the limits on what adaptation can achieve (informed by a new literature on loss and damage)
- Serious limitations on geophysical, biological, and socioeconomic data needed for adaptation at all geographic scales, including data on nature-society links and local (fine-scale) contexts (see WMO, 2008) and hazards
- Uncertainties about trends in societal, economic, and technological change with or without climate change, including the social and political underpinnings of effective adaptation
- Understanding the different impacts and adaptation responses for rapid and slow-onset disasters
- Developing the metrics for measuring and monitoring success in adaptation in each urban center:
  - Human deaths and injuries from extreme weather
  - Number of permanently or temporarily displaced people and others directly and indirectly affected
  - Impacts on properties, measured in terms of numbers of buildings damaged or destroyed
  - Impacts on infrastructure, services, and lifelines
  - Impacts on ecosystem services
  - Impacts on crops and agricultural systems and on disease vectors
  - Impacts on psychological well-being and sense of security
  - Financial or economic loss (including insurance loss)
  - Impacts on individual, household, and community coping capacities and need for external assistance.

8.2. Urbanization Processes, Climate Change Risks, and Impacts

8.2.1. Introduction

This section assesses the connections between urbanization and climate change in relation to patterns and conditions of climate risk, impact, and vulnerability. The focus is on urbanization's local, regional, and global environmental consequences and the processes that may lead to increased risk exposure, constrain people in high-risk livelihoods and residences, and generate vulnerabilities in critical infrastructure and services. Understanding urbanization and associated risk and vulnerability distributions is critical for an effective response to climate change threats and their impacts (Vale and Campanella, 2005; Bicknell et al., 2009; Solnit, 2009; Bulkeley, 2010; Romero-Lankao and Qin, 2011). It is also critical for the promotion of sustainable urban habitats and the transition to increased urban resilience. There is a particular interest here in the ability of cities to respond to environmental crises, and the resilience and sustainability of cities (Solecki et al., 2011; Solecki, 2012).

The section assesses the direct impacts of climate change on urban populations and urban systems. Together, with shifts in urbanization, these direct impacts change the profile of societal risk and vulnerability. Both can alter transition pathways that lead toward greater resilience and sustainable practices and the basis of how such practices are managed within a community. Understanding and acting on the connections between climate change and urbanization are also crucial because changes in one can affect the other. We investigate a range of direct impacts including those on physical and ecological systems, social and economic systems, and coupled human-natural systems. Where relevant to understanding, cascading impacts (where systems are tightly coupled) and secondary (indirect) impacts also are noted.

8.2.2. Urbanization: Conditions, Processes, and Systems within Cities

8.2.2.1. Magnitude and Connections to Climate Change

The spatial, temporal, and sustainability-related qualities of urbanization are important for understanding the shifting, complex interactions between climate change and urban growth. Given the significant and usually rising levels of urbanization (Section 8.1.3), a growing proportion of the world's population will be exposed to the direct impacts of climate change in urban areas (de Sherbinin et al., 2007; Revi, 2008; UN-HABITAT, 2011a). Urban centers in Africa, Asia, and Latin America with fewer than a million inhabitants are where most population growth is expected (UN DESA Population Division, 2012), but these smaller centers are "often institutionally weak and unable to promote effective mitigation and adaptation actions" (Romero-Lankao and Dodman, 2011, p. 114).

Urbanization alters local environments via a series of physical phenomena that can result in local environmental stresses. These include urban heat islands (higher temperatures, particularly at night, in comparison to outlying rural locations) and local flooding that can be exacerbated by climate change. It is critical to understand the interplay among the urbanization process, current local environmental change, and accelerating climate change. For example, in the past, long-term trends in surface air temperature in urban centers have been found to be associated with the intensity of urbanization (Kalnay et al., 2006; He et al., 2007; Ren et al., 2007; Stone, 2007; Fujibe, 2008, 2011; Jung, 2008; Rim, 2009; Sajjad et al., 2009; Santos and Leite, 2009; Tayanç et al., 2009; Kolokotroni et al., 2010; Chen et al., 2011; Iqbal and Quamar, 2011). Climate change can influence these microclimate and localized regional climate dynamics. For example, urbanization (micro scale to meso scale) can strengthen and/or increase the range of the local urban heat island (UHI) altering small-scale processes, such as a land-sea breeze effect, katabatic winds, etc., and modifying synoptic scale meteorology (e.g., changes in the position of high pressure systems in relation to UHI events). Climate modeling exercises indicate an "urban effect" that leads locally to higher temperatures. Building material properties are influential in creating different urban climate temperature regimes, which can alter energy demand for climate control systems in buildings (Jackson et al., 2010).

The dense nature of many large cities has a pronounced influence on anthropogenic heat emissions and surface roughness, linked to the level of wealth, energy consumption, and micro and regional climate conditions. Anthropogenic heat fluxes across large cities can average within a range of approximately 10 to 150 W m^{-2} but over small areas of the city can be three to four times these values or even more (Flanner, 2009; Allen et al., 2011). In London, an annual mean anthropogenic heat flux of 10.9 has been observed (Iamarino et al., 2012) with higher values in small areas of the city exceeding 100 (Allen et al., 2011) with a similar range found in Singapore (13 W m^{-2} in low-density residential areas and 113 W m^{-2} in high density commercial areas (Quah and Roth, 2012). Values locally greater than 1000 W m^{-2} have been calculated in Tokyo (Ichinose et al., 1999). Strong seasonal, diurnal, and meteorological variability in temperature also influence the level of significance of urbanization-related changes on specific cities.

The large spatial extent and significant amount of built environment of megacities (10 million or more inhabitants) can have significant impacts on the local and regional energy balance and associated weather, climate, and related environmental qualities such as air quality. Grimmond (2011) found increasing evidence that cities can influence weather (e.g., rainfall, lightning) through complex urban land use-weather-climate directional feedbacks (see also Ohashi and Kida, 2002). Spatially massive urban centers also can affect downwind locations by raising temperature and negatively impacting air quality (Bohnenstengel et al., 2011). Megacity impact on air flows has been modeled for New York and Tokyo (Holt and Pullen, 2007; Thompson et al., 2007; Holt et al., 2009). Megacity-coastal interactions may impact the hydrological cycle and pollutant removal processes through the development of fog, clouds, and precipitation in cities and adjoining coastal areas (Ohashi and Kida, 2002; Shepherd et al., 2002). Other modeling efforts define building density and design and the scale of urban development as important local determinants of the influence of urbanization on local temperature shifts (Trusilova et al., 2008; Oleson, 2012).

8.2.2.2. Spatiality and Temporal Dimensions

Spatial settlement patterns are a critical factor in the interactions among urbanization, climate-related risks, and vulnerability. One aspect is density, ranging from concentrated to dispersed, with most planned urban settlements decreasing in population density with distance from the core (Solecki and Leichenko, 2006; Seto et al., 2012). In cities with large fringe and unplanned settlements, this pattern can be reversed. In both cases, urban growth is experienced through horizontal expansion and sprawl (UN DESA Population Division, 2012), fostering extensive networks of critical infrastructure, which are frequently vulnerable to climate change (Rosenzweig et al., 2011; Solecki et al., 2011). Rapid urban population growth in the last decade also has been increasingly marked by growth in vertical density (high-rise living, and working), especially in Asia. Higher density living offers opportunities for resource conservation but also challenges for planning and urban management (Section 8.3.3).

Urbanization is associated with changing dimensions of migration and materials flows into and out of cities and also within them (Grimm et al., 2008). The level of increase (or in some cases decrease) of these conditions creates a dynamic quality of risk in cities. Rapidly changing cities must try to manage this growth through housing and infrastructure development while simultaneously understanding the relative impact of climate change. For example, in sub-Saharan Africa, the combination of relatively high population growth rates and increasing levels of urbanization brings a rise in exposure to climate change impacts (Parnell and Walawege, 2011). The conflation of local environmental change resulting from urbanization with climate change shifts makes the identification and implementation of effective adaptation strategies more difficult. Water shortages, for instance, already a chronic concern for many cities in low- and middle-income nations, typically worsen as the population and demand continue to grow (Muller, 2007). Climate change-related reductions or uncertainties in supply combine with this existing instability to create the conditions for greater management and governance crises (Milly et al., 2008; Gober, 2010).

8.2.2.3. Urbanization and Ecological Sustainability

The urbanization-climate change connection has important implications for ecological sustainability. Climate change can accelerate ecological pressures in cities, as well as interact with existing urban environmental, economic, and political stresses (Wilbanks and Kates, 2010; Leichenko, 2011). This is an especially important in a world where transgressions of key planetary boundaries such as climate change and biodiversity may take humanity out of the globe's "safe operating" space (Rockström et al., 2009, p. 1) into an unsafe and unpredictable future. A study by Trusilova et al. (2008) analyzes the urbanization-induced disturbances of the carbon cycle in Europe through land use change, local climate modification, and atmospheric pollution. This study shows that urban effects spread far beyond the city's boundaries and trigger complex feedback/responses in the biosphere (Trusilova et al., 2008). Urbanization changes land use cover, generally reduces the amount of ecologically intact land, and causes fragmentation of the remaining land, which reduces habitat value for species and increases the likelihood of further ecological degradation.

The linkage between urbanization, ecological sustainability, and climate change is well illustrated by the example of New Orleans. This city's geophysical vulnerability is shaped by its low-lying location, accelerating subsidence, rising sea levels, and heightened intensity and frequency of hurricanes—a combination of natural phenomena exacerbated by settlement decisions, canal development, loss of barrier wetlands, extraction of oil and natural gas, and the design, construction, and failure of protective structures and rainfall storage" (Wilbanks and Kates, 2010, p. 726; see also Ernstson et al., 2010). For cities in arid regions, already struggling with water shortages often in the context of rising demand, climate change may further reduce water availability because of shifts in precipitation and/or evaporation (Gober, 2010).

8.2.2.4. Regional Differences and Context-Specific Risks

Case studies and regional reviews assessing urban vulnerabilities to climate change have revealed diverse physical and societal challenges and large differences in levels of adaptive capacity (Hunt and Watkiss, 2011; Rosenzweig et al., 2011). Research on African cities (Simon, 2010; Kithiia, 2011; Castán Broto et al., 2013) has highlighted the lack of capacity and awareness of climate change, and often extremely high levels of vulnerability among the continent's large and rapidly growing urban poor populations. Other reviews have considered cities in Latin America (Hardoy and Romero-Lankao, 2011; Luque et al., 2013), North America (Zimmerman and Faris, 2011), Europe (Carter, 2011), and Asia (Alam and Rabbani, 2007; Kovats and Akhtar, 2008; Revi, 2008; Birkmann et al., 2010; Liu and Deng, 2011). The global distribution of urban risks is highly context specific, dynamic, and uneven among and within regions. Absolute exposure to extreme events over the next few decades will be concentrated in large cities and countries with urban populations in low-lying coastal areas, as in many Asian nations (McGranahan et al., 2007). Settlements located in river flood plains also are prone to flooding during extreme or persistent precipitation/severe storm conditions.

Many cities include dangerous sites, such as steep slopes, low lands adjacent to unprotected riverbanks, and ocean shorelines, and have structures that do not meet building codes (Hardoy et al., 2001; Pelling, 2003). Context-specific risks and associated vulnerability also relates to the socioeconomic status of residents. Women, children, health-compromised people, and the elderly in informal settlements are generally most vulnerable to climate change impacts. Poor access to infrastructure and transport, low incomes, limited assets, and dangerous locations can combine to put them at high risk from disasters (Moser and Satterthwaite, 2009).

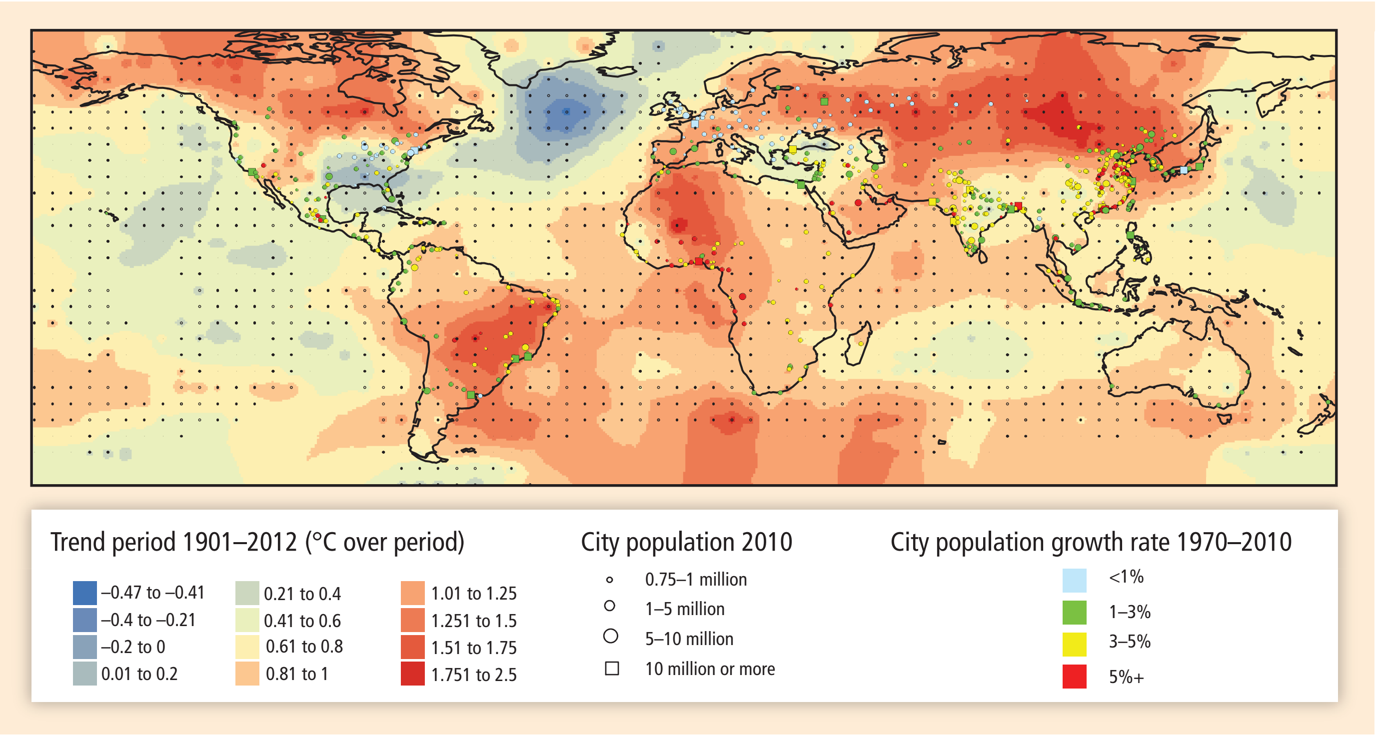
8.2.3. Climate Change and Variability Impacts: Primary (Direct) and Secondary (Indirect) Impacts

Climate change will lead to increased frequency, intensity, and/or duration of extreme weather events such as heavy rainfall, warm spells and heat events, drought, intense storm surges, and associated sea level rise (IPCC, 2007, 2012; Hunt and Watkiss, 2011; Romero-Lankao and Dodman, 2011; Rosenzweig et al., 2011). Several urban aspects of these changes are described below.

8.2.3.1. Urban Temperature Variation: Means and Extremes

The three maps in Figure 8-3 show where the world's largest urban agglomerations are concentrated in relation to changes in observed and projected temperature. Figure 8-3a shows the location of the largest urban agglomerations in 2010 against the backdrop of the observed history of climate-induced temperature rise (1901–2012). The dot for each urban agglomeration is color-coded according to its population

(a) Large urban agglomerations 2010 with observed climate change, trend period 1901–2012



(b) Large urban agglomerations 2025 with projected climate change for the mid-21st century using RCP2.6

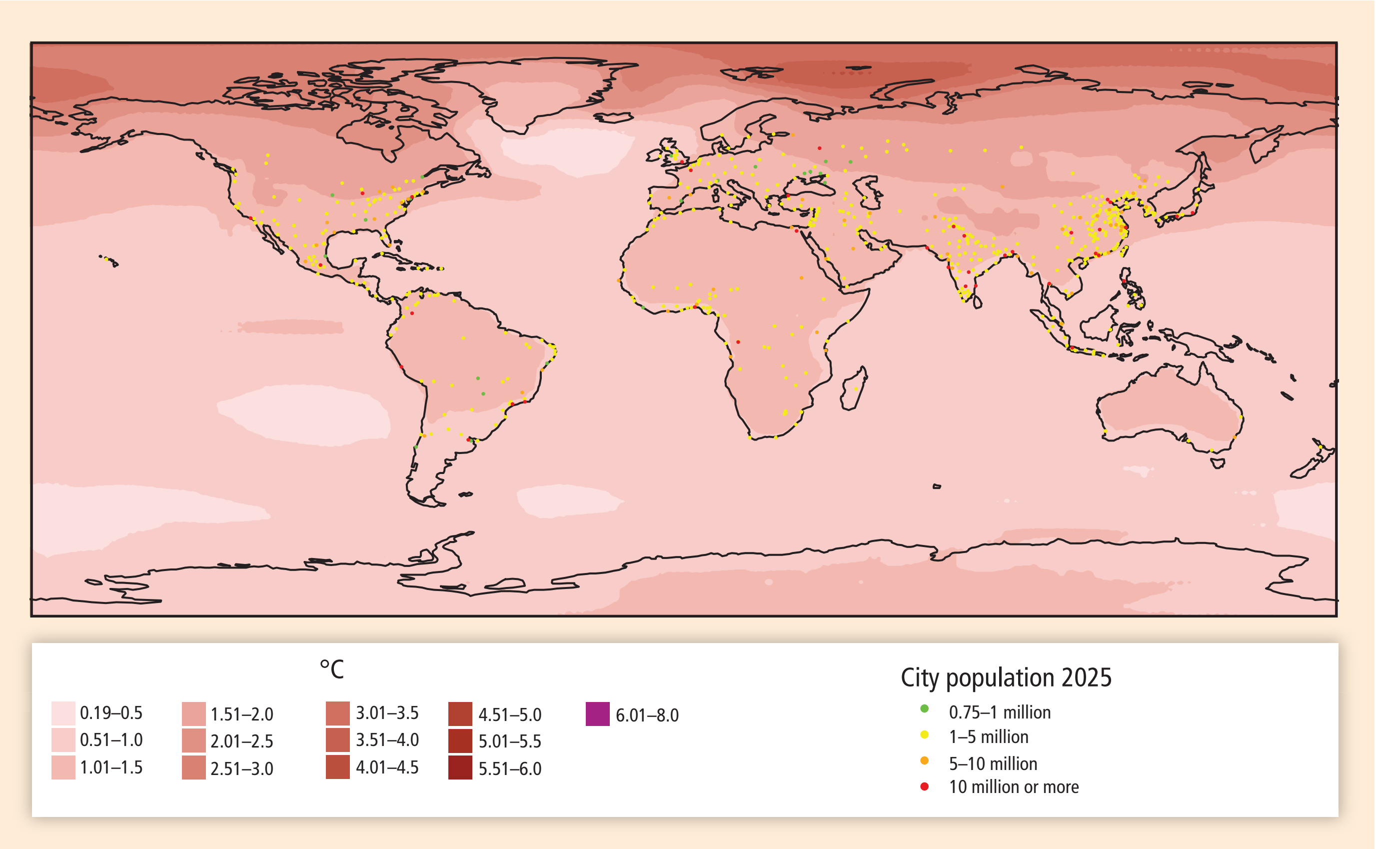
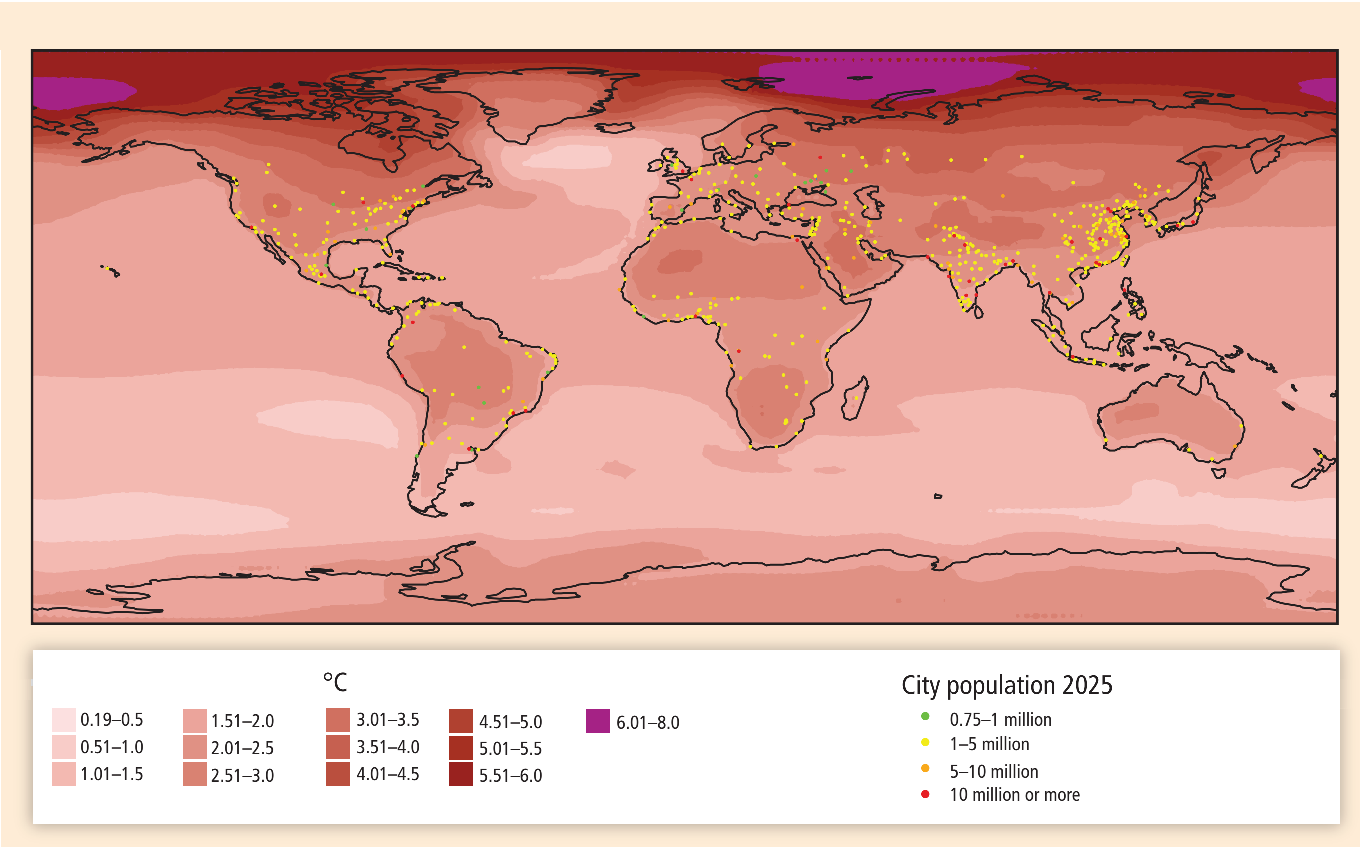


Figure 8-3 | Large urban agglomerations and temperature change (maps drawn from IPCC, 2013; urban agglomeration population and population growth data from UN DESA Population Division, 2012).

Continued next page →

Figure 8-3 (continued)

(c) Large urban agglomerations 2025 with projected climate change for the mid-21st century using RCP8.5



growth rate between 1970 and 2010. Those that had the most rapid population growth rates for these 4 decades are strongly clustered in Asia (especially in China and India) and in Latin America and sub-Saharan Africa (with many on the coast). This map highlights the temperature rise of greater than 1°C in areas in north and central Asia, western Africa, South America, and parts of North America, indicating the potential differential exposure of large cities to climate risk.

Figure 8-3b shows the location of the largest urban agglomerations according to projected populations for 2025 within the world map showing projected temperature changes for the mid-21st century, using Representative Concentration Pathway 2.6 (RCP2.6). This is a scenario with strong mitigation. Projected populations for urban agglomerations were not made up to 2050 because there is no reliable basis for making these. Each urban agglomeration's future population is much influenced by its economic performance and by social, demographic, economic, and political changes that cannot be predicted so far into the future. Assuming that almost all the large urban agglomerations in 2025 will still be large urban agglomerations in 2050, Figure 8-3b suggests that a number of large urban agglomerations in almost all continents, will be exposed to a temperature rise of greater than 1.5°C (over preindustrial levels) by mid-century, using the RCP2.6 scenario (IPCC, 2013).

Figure 8-3c shows a similar map showing projected temperature changes for the mid-21st century but using the RCP8.5 scenario. This scenario, based on unchanged current GHG emission trends by mid-century, shows that the bulk of the world's population living in the largest urban agglomerations (based on their 2025 populations) will be exposed to a minimum 2°C temperature rise over preindustrial levels, excluding urban heat island effects. By late-century, under the RCP2.6 scenario, a number of the urban agglomerations that were among the largest in 2025 will be exposed to temperature rise of up to 2.5°C over preindustrial levels (excluding urban heat island effects), especially in the high latitudes. This implies that mean temperature rise in some cities could be greater than 4°C. The RCP8.5 scenario by late century (with unchanged current GHG emission trends) shows that the bulk of the world's population living in large urban agglomerations will be exposed to a minimum 2.5°C temperature rise. Some cities in high latitudes experience a mean 3.5°C rise, or greater than 5°C when combined with UHI effects. Peak seasonal temperatures could be even higher. Temperature increases of 6°C to 8°C in the Arctic and temperature rise in Antarctica would contribute to sea level rise that would impact coastal cities across the world.

Increased frequency of hot days and warm spells will exacerbate urban heat island effects, causing heat-related health problems (Hajat et al., 2010) and, possibly, increased air pollution (Campbell-Lendrum and Corvalan, 2007; Blake et al., 2011), as well as an increase in energy demand for warm season cooling (Lemonsu et al., 2013). Conversely, widespread reduction in periods of very cold weather will mean a decline in heating demands (Mideksa and Kallbekken, 2010) and potential reduction in mortality from cold waves.

Climate change will modify UHIs in cities. Recent studies with physically based models (McCarthy et al., 2010; Früh et al., 2011; Oleson, 2012) show mixed signals, with reductions in UHI in many areas of the world and increases in some in response to climate change simulations. London's annual number of nights with heat islands stronger than 4ºC has increased by 4 days per decade since the late 1950s; meanwhile, the average nocturnal heat island intensity rose by approximately 0.1°C per decade over the same period (Wilby, 2007). Projections suggest that by 2050, London's nocturnal UHI in August could rise another 0.5°C, representing a 40% increase in the number of nights with intense UHI episodes (Wilby, 2007). However, McCarthy et al. (2011), looking specifically at London and Manchester, found 0.1ºC or less (T_{min}) increase in expected UHI by the 2050s. Future projections of UHI under global warming conditions were also conducted for Tokyo, where a potential increase of the UHI intensity of 0.5ºC was defined (Adachi et al., 2012). Adachi et al. (2012) model an increase in UHI from 1.0ºC to 1.5ºC by the 2070s. In addition to the greater UHI intensity, air temperature in August is projected to increase about 2ºC by the 2070s according to an average of five Global Climate Models (GCMs) under the *Special Report on Emissions Scenarios* (SRES) A1B scenario (the range of uncertainty in GCMs is about 2ºC).

Climate change in New York City is expected to increase extended heat waves, thus exacerbating existing UHI conditions (Rosenzweig et al., 2009). Increased nighttime minimum temperatures are associated with increased cooling demand and health-related stresses. For cities in India, the implications of future climate for connections between urbanization and the development of UHI have been defined (Mohan et al., 2011a,b, 2012). Overall, the current trend of increasingly frequent extreme events is expected to increase with climate change (Manton, 2010). Comparison of the annual mean minimum temperatures of two stations in Delhi (Safdarjung and Palam) since the 1970s shows night temperature trends synchronizing with the city's pace of expansion (Mohan et al., 2011a).

8.2.3.2. Drought and Water Scarcity: Means and Extremes

Drought can have many effects in urban areas, including increases in water shortages, electricity shortages (where hydropower is a source), water-related diseases (through use of contaminated water), and food prices and food insecurity from reduced supplies. These may all contribute to negative economic impacts and increased rural to urban migration (Vairavamoorthy et al., 2008; Herrfahrdt-Pähle, 2010; Farley et al., 2011). An estimated 150 million people currently live in cities with perennial water shortage, defined as less than 100 liters per person per day of sustainable surface and groundwater flow within their urban extent. Averages across all climate change scenarios, noting the role of demographic growth, suggest a large increase in this number, possibly up to 1 billion by 2050 (McDonald et al., 2011).

8.2.3.3. Coastal Flooding, Sea Level Rise, and Storm Surge

Sea level rise represents one of the primary shifts in urban climate change risks, given the increasing concentration of urban populations in coastal locations and within low-elevation zones (McGranahan et al., 2007). The new IPCC estimates for global mean sea level rise are for between 26 and 98 cm by 2100; this is higher than the 18 to 59 cm projected in AR4 (IPCC, 2013). Rising sea levels, the associated coastal and riverbank erosion, or flooding in conjunction with storm surge could have widespread effects on populations, property, and coastal vegetation and ecosystems, and present threats to commerce, business, and livelihoods (Nicholls, 2004; Dossou and Gléhouenou-Dossou, 2007; Zanchettin et al., 2007; El Banna and Frihy, 2009; Carbognin et al., 2010; Pavri, 2010; Hanson et al., 2011). This is well illustrated by several large-scale recent disasters including Hurricane Sandy in the New York metropolitan region. Lowland areas in coastal cities such as Lagos, Mombasa, or Mumbai are usually more at risk of flooding, especially where there is less provision for drainage (Awuor et al., 2008; Revi, 2008; Adelekan, 2010). Structures on infilled soils in the lowlands of Lagos and Mumbai are more exposed to risks of flood hazards than similar structures built on consolidated materials (Awuor et al., 2008; Revi, 2008; Adelekan, 2010). Many near coastal cities such as Dhaka have sites at risk from both riverine and coastal storm surge (Mehrotra et al., 2011a).

Cities with extensive port facilities and large-scale petro-chemical and energy-related industries are especially vulnerable to risks from increased flooding (Hallegatte et al., 2013). Hanson et al. (2011) estimate the change in flooding by the 2070s in the exposure of large port cities to coastal flooding with scenarios of socioeconomic growth, sea level rise and heightened storm surge, and subsidence. They find that with a 0.5 m rise in sea level, the population at risk could more than triple while asset exposure is expected to increase more than 10-fold. The "top 20" cities identified for both population and asset exposure to coastal flooding in both the current and 2070 rankings are spread across low-, middle-, and high-income nations, but are concentrated in Asian deltaic cities. They include: Mumbai, Guangzhou, Shanghai, Miami, Ho Chi Minh City, Kolkata, New York, Osaka-Kobe, Alexandria, Tokyo, Tianjin, Bangkok, Dhaka, and Hai Phong. Using asset exposure as the metric, cities in high-income nations and in China figure prominently: Miami, New York City, Tokyo, and New Orleans as well as Guangzhou, Shanghai, and Tianjin. Detailed site specific studies can define the local level of sea level rise and other local factors such as harbor development, dredging and erosion, groundwater withdrawal, and subsidence and other factors.

8.2.3.4. Inland Flooding, Hydrological and Geo-Hydrological Hazards at Urban Scale

Exposure to climate related hazards will vary with differences in the geomorphologic characteristics of cities (Luino and Castaldini, 2011). Heavy rainfall and storm surges would impact urban areas through flooding, which in turn can lead to the destruction of properties and public infrastructure, contamination of water sources, water logging, loss of business and livelihood options, and increase in water-borne and water-related diseases, as noted in wide range of studies (de Sherbinin et al., 2007; Dossou and Gléhouenou-Dossou, 2007; Douglas et al., 2008; Kovats and Akhtar, 2008; Revi, 2008; Roberts, 2008; Hardoy and Pandiella, 2009; Nie et al., 2009; Adelekan, 2010; Sharma and Tomar, 2010; Shepherd et al., 2011). Case studies of inland cities have considered the elevated risk of flooding due to climate change, as in Kampala (Lwasa, 2010) and travel disruptions in Portland (Chang et al., 2010). There have been significant research attempts to improve modelling of the frequency and condition of extreme precipitation events and resulting flooding (Nelson et al., 2008; Olsson et al., 2009; Onof and Arnbjerg-Nielsen, 2009; Sen, 2009; Ranger et al., 2011).

The review on the world-wide impacts of climate change on rainfall extremes and urban drainage by Willems et al. (2012) has shown that typical increases in rainfall intensity at small urban hydrology scales range from 10% to 60% from control periods in the recent past (typically 1961–1990) up to 2100. These changes in extreme short-duration rainfall events may have significant impacts for urban drainage systems and pluvial flooding. Results so far indicate more problems with sewer sub-charging, sewer flooding, and more frequent combined sewer overflow (CSO) spills. Extreme rainfall changes in the range of 10 to 60% may lead to changes in flood and CSO frequencies and volumes in the range 0 to 400% depending on system characteristics. This is because floods and overflows, when runoff or sewer flow thresholds are exceeded, can react to rainfall (changes) in a highly nonlinear way (Willems and Vrac, 2011; Willems et al., 2012; Arnbjerg-Nielsen et al., 2013; Willems, 2013).

8.2.3.5. Emerging Human Health, Disease, and Epidemiology Issues in Cities

WHO and WMO (2012) and Barata et al. (2011) note that climate change may affect the future social and environmental determinants of health, including clean air, safe drinking water, sufficient food, and secure shelter. There is good evidence that temperature extremes (heat and cold) affect health, particularly mortality rates (see Section 11.2.2). Increased warming and physiological stress on human comfort level is predicted in a variety of cities in subtropical, semiarid, and temperate sites (Thorsson et al., 2011; Blazejczyk et al., 2012); see also Figure 8-3. For more discussion on cities and impacts of increased warming in specific regions, see the regional chapters (Chapters 21 to 30).

Recent studies have illustrated the impact of heat stress on urban populations in low- and middle-income countries (see, e.g., Burkart et al., 2011, for Bangladesh and Egondi et al., 2012, for children in Nairobi's informal settlements). Hot days are known to have significant impacts on health that can be exacerbated by both drought conditions and high humidity. Studies in high-income countries show the elderly more vulnerable to heat-related mortality (see Oudin Åström et al., 2011, for a review of this). In urban settings where child mortality is high, extreme temperatures have been shown to have an impact on mortality (e.g., Egondi et al., 2012). People in some occupations are more at risk, as they are exposed to higher temperatures for long durations (see Hoa et al., 2013) and low-income households are more at risk when heat waves disrupt or limit income-earning opportunities (Kovats and Akhtar, 2008, see also Section 11.2.7 for more detailed discussion of occupational heat stress).

Climate change has implications for urban air quality (Athanassiadou et al., 2010), air pollution, and health policy (WGI AR5 Chapter 11). The impacts on urban air quality in particular urban areas are highly uncertain and may include increases and decreases of certain pollutants (Jacob and Winner, 2009; Weaver et al., 2009). Urban air quality in most cities already is compromised by localized air pollution from transport and industry, and often commercial and residential sources. Emerging literature shows strong evidence that climate change will generally increase ozone in the USA and Europe, but that the pattern of that change is not clear, with some areas increasing and some decreasing (Katragkou et al., 2011; Lam et al., 2011). The effects on particulate matter (PM) are also unclear, as are the effects on ozone and PM outside of the USA and Europe (Dawson et al., 2013).

The incidence of asthma exacerbation may be affected by climate change-related increases in ground level ozone exposures (Kinney, 2008; Gamble et al., 2009; O'Neill and Ebi, 2009; Reid et al., 2009; Barata et al., 2011); other pollutants may also be affected, particularly in cities with PM10 and ozone levels far above WHO guidelines (WHO, 2011). Climate change may change the distribution, quantity, and quality of pollen in urban areas, as well as the timing and duration of pollen seasons. WHO and WMO (2012) notes that diarrheal diseases, malnutrition, malaria, and dengue are climate sensitive and, in the absence of appropriate adaptation, could be adversely affected by climate change (see Chapter 11).

8.2.4. Urban Sectors: Exposure and Sensitivity

This section assesses how the observed and forecast direct impacts of climate change influence the exposure of city residents, buildings, infrastructure, and systems to risk. It considers key affected sectors and populations and possible interrelations. Direct impacts include all costs and losses attributed to the impact of hazard events, but exclude systemic impacts, for example, on urban economies through price fluctuations following a disaster or the impact of disaster losses on production chains (UN ECLAC, 1991). Both the temporal and spatial scales of the shifts in climate risk across cities and urbanizing sites in the next few decades are considered. In addition, we analyze the change in the scale and character of risks in cities, as climate extremes, means, and long-term trends (e.g., sea level rise) change.

Climate change will have profound impacts on a broad spectrum of city functions, infrastructure, and services and will interact with and may exacerbate many existing stresses. These impacts can occur both *in situ* and through long-distance connections with other cities and rural sites of resource production and extraction (Wackernagel et al., 2006; Seto et al., 2012). The interaction between climate change and existing environmental stresses can lead to a range of synergies, challenges, and opportunities for adaptation with complex interlinkages and often highly uncertain or nonlinear processes (Ernstson et al., 2010). For example, the 2007 floods in the city of Villahermosa, which covered two-thirds of Tabasco State in Mexico, had serious consequences for the city's economic base, with damages and losses equivalent to 30% of the state's annual GDP (CEPAL, 2008). The flood that struck the Chao Phraya River in 2011 caused a high loss of life and damages to many companies and several industrial estates in Bangkok (estimated local damage and loss was 3.5 trillion yen), but it also disrupted global scale industrial supply chains (Komori et al., 2012). Urban centers serving prosperous agricultural regions are particularly sensitive to climate change if water supply or particular crops are at risk. In Naivasha, Kenya, drought threatens high-value export-oriented horticulture (Simon, 2010). Urban centers that serve as major tourism destinations may suffer when the weather becomes stormy or excessively hot and leads to a loss of revenue. Recent assessments have projected the rising population and asset exposure in large port cities (Munich Re, 2004; Hanson et al., 2011; see also Section 8.2.3.3), alongside case studies in Copenhagen (Hallegatte et al., 2011b) and Mumbai (Ranger et al., 2011). By 2070, the exposed assets in cities such as Ningbo (China), Dhaka (Bangladesh), and Kolkata (India) may increase by more than 60-fold (Hanson et al., 2011).

Infrastructure will similarly be affected by systemic and cascading climate risks (Hunt and Watkiss, 2011). Climate stresses, particularly extreme events, will have effects across interconnected urban systems, within and across multiple sectors (Gasper et al., 2011). The cascading effects are especially evident in the water, sanitation, energy, transport, and communications sectors, owing to the often tightly coupled character of urban infrastructure systems (see Rosenzweig and Solecki, 2010, for a discussion of this for New York City). The U.S. National Climate Assessment effort has looked at the impacts of climate change on infrastructure, considering the water, land, and energy nexus, as well as on a large number of industries (Skaggs et al., 2012; Wilbanks et al., 2012). These systemic cascades can have both direct and indirect economic impacts (Hallegatte et al., 2011b; Ranger et al., 2011), which can extend from the built environment to urban public health (Frumkin et al., 2008; Keim, 2008). A critical element is the impact for infrastructure investments with long operational lives, in some cases 100 years or more (Hallegatte et al., 2011a). In low- and most middle-income cities, very large additional investment is needed to address deficits in infrastructure and services; without this investment, making the short- to long-term trade-off to improve resilience is difficult (Dodman and Satterthwaite, 2009). This is an opportunity for "climate smart" infrastructure planning that considers how to combine pro-poor development and climate change adaptation and mitigation. This is a more difficult task for cities such as New York with dense aging infrastructure and materials that "may not be able to withstand the projected strains and stresses from a changing climate" (Zimmerman and Faris, 2010, p. 63). These cities also have the opportunity, when replacing aging infrastructure, to integrate climate considerations into the new infrastructure decision-making processes.

8.2.4.1. Water Supply, Wastewater, and Sanitation

Water and sanitation systems affect household well-being and health, as well as influencing urban economic activities, energy demands, and the rural-urban water balance (Gober, 2010). Climate change will impact residential water demand and supply and its management (O'Hara and Georgakakos, 2008). Among the projected impacts are altered precipitation and runoff patterns in cities, sea level rise and resulting saline ingress, constraints in water availability and quality, and heightened uncertainty in long-term planning and investment in water and waste water systems (Muller, 2007; Fane and Turner, 2010; Major et al., 2011). Local government departments and utilities responsible for water supply and waste water management must confront these new climatic patterns and major uncertainties in availabilities and learn to respond to dynamic and evolving sets of constraints (Milly et al., 2008).

Climate change will increase the risk and vulnerability of urban populations to reductions in groundwater and aquifer quality (e.g., Praskievicz and Chang, 2009; Taylor and Stefan, 2009), subsidence, and increased salinity intrusion. High levels of groundwater extraction have led to serious subsidence problems in cities such as Bangkok (Babel et al., 2006) and Mexico City (Romero-Lankao, 2010), which damage buildings, fracture pipes, and can increase flood risks (see also Jha et al., 2012). This problem can be compounded in coastal cities when saline intrusion reduces groundwater quality and erodes structures.

In many rapidly developing cities, the impact of climate change on water supplies will interact with growing population, growing demand, and economic pressures, potentially heightening water stress and negative impacts on the natural resource base, with effects for water quality and quantity. Caribbean nations, for example, with their expanding middle-class urban population, face sharply raised demands for water and the associated challenges of managing runoff, storm water, and solid wastes. Projected reductions in rainfall amounts at specific times in particular locations would aggravate such water stresses (Cashman et al., 2010). In Shanghai, climate change is expected to bring decreased water availability as well as flooding, groundwater salinization, and coastal subsidence. The city's population of 17 million is projected to continue expanding, often within areas that are "likely increasingly flood-prone" (de Sherbinin et al., 2007, p. 60). Groundwater depletion has contributed to land subsidence in these already vulnerable areas, reinforcing the water stresses and risks of erosion (de Sherbinin et al., 2007). In several large Andean cities, including Lima, La Paz, and Quito, declining volumes of glacial melt water have been observed, with expected further declines (Buytaert et al., 2010; Chevallier et al., 2011).

Several studies estimate how climate change will alter relationships among water users, exacerbating tensions and conflicts between the various end users (residential, commercial, industrial, agricultural, and infrastructural) (Roy et al., 2012; Tidwell et al., 2012). In small and mid-sized African cities, the effect of flooding on well water quality is a growing concern (Cissé et al., 2011). Floods, droughts, and heavy rainfall have also impacted agriculture and urban food sources, and can exacerbate food and water scarcity in urban areas (Gasper et al., 2011). But not all water systems are projected to experience negative impacts. Chicago's Metropolitan Water Reclamation District (MWRD) found that reduced precipitation due to climate change would decrease pumping and general operations costs, as sewers will contain less rainwater in drier seasons (Hayhoe et al., 2010).

Wastewater and sanitation systems will be increasingly overburdened during extreme precipitation events if attention is not paid to maintenance, the limited capacity of drainage systems in old cities, or lack of provision for drainage in most unplanned settlements and in many urban centers (Wong and Brown, 2009; Howard et al., 2010; Mitlin and Satterthwaite, 2013). In the city of La Ceiba, Honduras, stakeholders concluded that urban drainage and improved management of the Rio Cangrejal watershed were top priorities for protection against projected climate change impacts; the city lacks a stormwater drainage system but experiences regular flooding (Smith et al., 2011).

Flooding is often made worse by uncontrolled city development that builds over natural drainage channels and flood plains or by a failure to maintain drainage channels (often blocked by solid wastes where waste collection is inadequate). These problems are most evident in cities where there are no drains or sewers to help cope with heavy precipitation (Douglas et al., 2008) and no service to collect solid wastes (in many cities in low-income nations, less than half the population has regular solid waste collection; see Hoornweg and Bhada-Tata, 2012). Many cities in high-income nations also face challenges. An analysis of three cities in Washington State, assessing future streamflows and peak discharges, concluded that "concern over present (drainage) design standards is warranted" (Rosenberg et al., 2010, p. 347). Climate change was identified as a key driver affecting Britain's future sewer systems. According to the model used, the volume of sewage released to the environment by combined sewage overflow spills and flooding was projected to increase by 40% (Tait et al., 2008).

8.2.4.2. Energy Supply

Energy exerts a major influence on economic development, health, and quality of life. Any climate change-related disruption or unreliability in power or fuel supplies can have far-reaching consequences, affecting urban businesses, infrastructure, services (including healthcare and emergency services) and residents, as well as water treatment and supply, rail-based public transport, and road traffic management (Jollands et al., 2007; Finland Safety Investigations Authority, 2011; Halsnæs and Garg, 2011; Hammer et al., 2011).

Past experiences with power outages indicate some of the knock-on effects (Chang et al., 2007). New York City's blackout of 2003 lasted 28 hours and halted mass transport, surface vehicles due to signaling outages, and water supply (Rosenzweig and Solecki, 2010). A review of climate change impacts on the electricity sector (Mideksa and Kallbekken, 2010) projects reductions in the efficiency of water cooling for large electricity-generating facilities, changes in hydropower and wind power potential, and changing demand for heating or cooling in the USA and Europe. Low-income households in Chittagong use candles or kerosene lamps during frequent power outages; this was found to disturb children's studies, increase expenses, and overheat homes (Rahman et al., 2010).

Climate change will alter patterns of urban energy consumption, particularly with respect to the energy needed for cooling or heating (for a review, see Mideksa and Kallbekken, 2010). Climate change will bring increases in air conditioning demand and in turn heightened electricity demand (Radhi, 2009; see also Hayhoe et al., 2010, for a discussion of this in relation to Chicago). In temperate and more northern regions, winter temperature increases may decrease energy demand (Mideksa and Kallbekken, 2010). In most cases within individual cities, potential increases in summertime electricity demand from climate change will exceed reductions in winter energy demand reductions (Hammer et al., 2011). Less is known about the demand-side impacts in low- and lower-middle-income nations, where large sections of the urban population still lack access to electricity (Johansson et al., 2012; Satterthwaite and Sverdlik, 2012). Most of these nations are expected, as noted, to have increased mean temperatures or rising frequency of heat waves (IPCC, 2007).

Many cities' economies will be affected if water scarcity and variability interrupt hydropower supplies. For instance, reductions in hydroelectric generation will have impacts on the economies of many urban centers in Brazil as well as in neighboring countries (de Lucena et al., 2009, 2010; Schaeffer et al., 2011). Cities in sub-Saharan Africa often rely on hydropower for their electricity, and failures in supplies can lead "to a more general 'urban failure'" (Muller, 2007, p. 106). Laube et al. (2006) discuss water shortages in Ghana following low precipitation periods, and the potential for competition between hydropower and water provision, including to downstream urban centers. Declining water levels in the Hoover Dam have raised the possibility that Los Angeles will lose a major power source, and that Las Vegas will face a severe decline in drinking water availability (Gober, 2010).

Summer heat waves, with spikes in demand for air conditioning, can result in brownouts or blackouts (Mirasgedis et al., 2007; Mideksa and Kallbekken, 2010). Cities in the temperate regions of Australia already experience regular blackouts on hot summer days, largely due to residential air-conditioner use (Maller and Strengers, 2011). Research in Boston suggested that rising energy demands in hotter summers have meant a "disproportional impact on (the) elderly and poor, increased energy expenditures; loss of productivity and quality of life" (Kirshen et al., 2008, p. 241). Any increase in the frequency or intensity of storms may disrupt electricity distribution systems because of the collapse of power lines and other infrastructure (Rosenzweig et al., 2011; see also Chapter 10).

8.2.4.3. Transportation and Telecommunications

Climate change-related extreme events will affect urban transportation and telecommunication infrastructure, including a variety of capital stock, such as bridges and tunnels, roads, railways, pipelines, and port facilities, data sensors, and wire and wireless networks (Koetse and Rietveld, 2009; Hallegatte et al., 2011a; Jacob et al., 2011; Major et al., 2011). In the Gulf Coast region of the United States, 27% of major roads, 9% of rail lines, and 72% of ports are at or below 122 cm (4 ft) in elevation. With a storm surge of 7 m (23 ft), more than half the area's major highways, almost half the rail miles, 29 airports, and virtually all the ports are subject to flooding (Savonis et al., 2008). Assessing possible disruptions of transport networks within cities and urban systems is critical. Loss of telecommunication access during extreme weather events can inhibit disaster response and recovery efforts because of its critical role in providing logistical support for such activity (Jacob et al., 2011).

Ports are central to international trade and climate change poses substantial challenges related to exposed locations in coastal zones, low-lying areas, and deltas; long lifespans of key infrastructure and interdependencies with trade, shipping, and inland transport services that are also vulnerable (Oh and Reuveny, 2010; Asariotis and Benamara, 2012). Hurricane Sandy crippled the New York region, leading to a week-long shut-down of one of the largest container ports in the USA (Hallegatte et al., 2013).

Large sections of the urban population in low- and middle-income nations live in settlements without all-weather roads and paths that allow for emergency vehicle access and rapid evacuation. For instance, in Chittagong, Bangladesh, extremely narrow roads limit emergency access to most informal neighborhoods, exacerbating health and fire risks (Rahman et al., 2010). In Lagos's informal settlements, a 2006 resident survey ranked roads second to drainage in terms of needed facilities (Adelekan, 2010). Evacuations in low-income areas may also be hampered by hazardous locations, absence of public transport, and inadequate governance. Following the 2003 and 2006 floods in Santa Fe, Argentina, the lack of information and official evacuation mechanisms prevented timely responses; some residents also chose to stay in their homes to protect their possessions from looters (Hardoy and Pandiella, 2009).

Low-income urban residents can also be profoundly affected during and after extreme weather events that damage critical public transit links, prevent access to work, and heighten exposure to health risks. Interviews in Georgetown, Guyana, found that the limited transport access of low-income households during floods made them more prone to losing time from work or school, compared to wealthier households. Poorer households rarely owned cars, and wading barefoot through floodwaters exposed them to water-borne pathogens (Linnekamp et al., 2011). Some studies find urban women walk or use public transport more than men (World Bank, 2010c); hence, the gendered impact of transport disruptions may merit greater consideration (UN-HABITAT, 2011a; Levy, 2013).

The literature on urban transport and climate change focuses more on mitigation, with less attention to vulnerability, impacts, and adaptation (Hunt and Watkiss, 2011). Existing studies on impacts are often limited to the short-term demand side, particularly in passenger transport (Koetse and Rietveld, 2009). However, climate change creates several challenges for transport systems. The daily functioning of most transport systems is already sensitive to fluctuations in precipitation, temperature, winds, visibility, and for coastal cities, rising sea levels with the associated risks of flooding and damages (Love et al., 2010). Transport is highly vulnerable to climate variability and change, and the economic importance of transport systems has increased with the rise of just-in-time delivery methods, heightening the risk of losses due to extreme weather (Gasper et al., 2011).

In addition to adapting road transport, cities should ensure bridges, railway cuttings, and other hard infrastructure is resilient to climate change over their service lifespan (Jaroszweski et al., 2010). Few studies have examined the effects of climate change on railways, but rail system failures are known to be related to high temperatures, icing, and storms (Koetse and Rietveld, 2009; see Dobney et al., 2008, for future heat-related delays in UK railways; also Palin et al., 2013, offers a broad discussion of climate change effects on the UK rail network). Very few studies have examined the vulnerability of air- and sea-borne transport and infrastructure, but climate change could mean more and lengthier weather-related delays and disruption (Eurocontrol, 2008; Becker et al., 2012).

Loss of sea ice can benefit some cities by increasing opportunities for developing road networks or ports. However, it may be costly to adapt road, air, and water transport networks to the known environmental risks associated with such redevelopment (Larsen et al., 2008). For industries and communities in northern Canada, reduced freshwater-ice levels creates longer shipping seasons and could also promote new seaports in marine environments. But thawing of permafrost can also result in instability and major damage to roads, infrastructure, and buildings in and around northern cities and towns, and inland towns will require sizable investments to replace winter ice roads with land-based roads (Prowse et al., 2009).

The direct impacts of extreme weather on transport are more easily assessed than the indirect impacts or possible knock-on effects between systems. Studies have often examined the direct impacts of flooding on transport infrastructure, but the indirect costs of delays, detours, and trip cancellation may also be substantial (Koetse and Rietveld, 2009). Mumbai's 2005 floods caused injuries, deaths, and property damage but also serious indirect impacts as most city services were shut down without contact via rail, road, or air (Revi, 2005). Transport and other urban infrastructure networks are often interdependent and located in close proximity to one another, yet only a few assessments have considered the joint impacts (Kirshen et al., 2008; Hayhoe et al., 2010).

Transportation systems are critical for effective disaster response—for example, where populations have to be evacuated prior to an approaching storm or where provision is urgently needed for food, water, and emergency services to affected populations.

Key elements in cities' communications systems may have to be strengthened—for instance, to avoid masts toppling due to strong winds and electrical support facilities that need to be moved or protected against flooding (Zimmerman and Faris, 2010, p. 74). New York City's dispersed communications network faces several climate-related risks. Electrical support facilities can be flooded; cell phone towers can topple in strong winds or become corroded as sea levels rise (Zimmerman and Faris, 2010). In Alaska, telecommunications towers are settling as a result of warming permafrost (Larsen et al., 2008). Emergencies may generate a demand for communications that exceeds systems' capacities. During the extreme rainfall event in 2005, Mumbai's telecommunications networks ceased to function due to a mix of overload, shut down of the power system, and lack of diesel supplies for generators (Revi, 2005).

8.2.4.4. Built Environment, and Recreation and Heritage Sites

Housing ideally provides its occupants with a comfortable, healthy, and secure living environment and protects them from injuries, losses, damage, and displacement (Haines et al., 2013). For many low-income households, livelihoods also depend on home-based enterprises, and housing is key to protecting their assets and preventing disruption of their incomes. Decent housing has particular importance for vulnerable groups, including infants and young children (Bartlett, 2008), older residents, or those with disabilities or chronic health conditions.

Urban housing is often the major part of the infrastructure affected by disasters, according to Jacobs and Williams (2011). Extreme events such as cyclones and floods inflict a heavy toll, particularly on structures built with informal building materials and outside of safety standards (UNISDR, 2011). Dhaka's 1998 floods damaged 30 percent of the city's units; of these, more than two-thirds were owned by the lower-middle classes and the poorest (Alam and Rabbani, 2007). Adelekan (2012) shows that a relatively modest increase in wind speeds during storms caused widespread damage in central Ibadan. Relative to the preceding decade, the period from 1998 to 2008 showed higher mean maximum wind gusts and more frequent windstorms with peak gusts greater than 48 knots, and the impacts were severe in part because of the high concentration of residents in damaged buildings. Increased climate variability, warmer temperatures, precipitation shifts, and increased humidity will accelerate the deterioration and weathering of stone and metal structures in many cities (Grossi et al., 2007; Thornbush and Viles, 2007; Smith et al., 2008; Bonazza et al., 2009; Stewart et al., 2011).

Recreational sites such as parks and playgrounds will also be affected. In New York City, these are defined as critical infrastructure and are often located in low elevation areas subject to storm surge flooding (Rosenzweig and Solecki, 2010). Little research has examined the effects on urban tourism in particular (Gasper et al., 2011).

The increased risks that climate change brings to the built environment (Spennemann and Look, 1998; Wilby, 2007) also apply to built heritage. This has led to the Venice Declaration on Building Resilience at the Local Level Towards Protected Cultural Heritage and Climate Change Adaptation Strategies, which brings together UNESCO, UN-HABITAT, EC, and individual city mayors. An example is Saint-Louis in Senegal, a coastal city and World Heritage Site on the mouth of the Senegal river, which has frequent floods and large areas at risk from river and coastal flooding. There are initiatives to reduce flooding risks and relocate families from locations most at risk, but the local authority has very limited investment capacity (Diagne, 2007; Silver et al., 2013).

8.2.4.5. Green Infrastructure and Ecosystem Services

Climate change will alter ecosystem functions affected by changes in temperature and precipitation regimes, evaporation, humidity, soil moisture levels, vegetation growth rates (and allergen levels), water tables and aquifer levels, and air quality. It will also accentuate the value of ecosystems services and green infrastructure for adaptation. "Green infrastructure" refers to interventions to preserve the functionality of existing green landscapes (including parks, forests, wetlands, or green belts), and to transform the built environment through phytoremediation and water management techniques and by introducing productive landscapes (Foster et al., 2011b; La Greca et al., 2011; Zhang et al., 2011). These can influence the effectiveness of pervious surfaces used in storm water management, green/white/blue roofs, coastal marshes used for flood protection, urban agriculture, and overall biomass production. Mombasa will experience more variable rainfall as a result of climate change, making the expansion of green infrastructure more difficult (Kithiia and Lyth, 2011). Trees in British cities will be increasingly prone to heat stress and attacks by pests, including new non-native pathogens and pests that can survive under warmer or wetter conditions (Tubby and Webber, 2010). Urban coastal wetlands will be inundated with sea level rise. In New York City, remnant coastal wetlands will be lost to sea level rise because bulk heading and intensive coastal development will prevent their natural movement inland (Gaffin et al., 2012).

8.2.4.6. Health and Social Services

The effects of climate change will also be evident across urban public services including health and social care provision, education, police, and emergency services (Barata et al., 2011, see also Chapter 11). Most urban centers in low-income nations and many in middle-income nations lack adequate social and public service provision (Bartlett, 2008; UN-HABITAT, 2003a) while higher-income cities are only beginning to consider climate change in their health or disaster management plans (Brody et al., 2010).

Although there are few studies on adapting education, police, or other key services, a growing public health literature has discussed multi-sectoral adaptation strategies (Huang et al., 2011). Cities' existing public health measures provide a foundation for adapting to climate change, such as heat warning systems or disease surveillance (McMichael et al., 2008; Bedsworth, 2009). Negative climate impacts have been highlighted on some of the most vulnerable in society—including children (Ebi and Paulson, 2010; Sheffield and Landrigan, 2011; Watt and Chamberlain, 2011), the elderly (White-Newsome et al., 2011; Oven et al., 2012), and the severely disadvantaged (Ramin and Svoboda, 2009; see also Chapter 11).

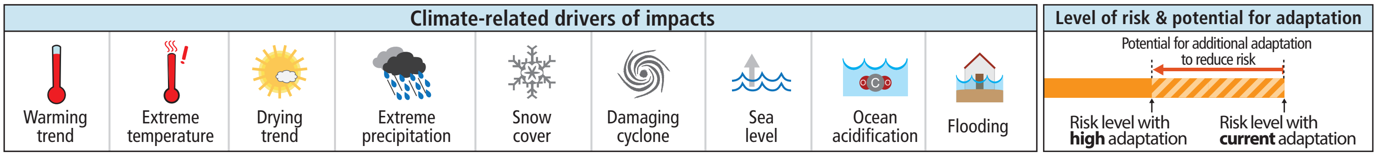
8.2.5. Urban Transition to Resilience and Sustainability

The question of how to promote increased resilience and enhanced sustainability in urban areas (as illustrated in Table 8-2) has become a central research topic and policy consideration. It is well recognized that climate change risks affect this process by heightening uncertainties and altering longstanding patterns of environmental risk in cities, many of which continue to face other significant stressors such as rapid population growth, increased pollution, resource demands, and concentrated poverty (Wilbanks and Kates, 2010; Mehrotra et al., 2011a). This section discusses how climate change increasingly affects municipal decision-making frames and alters local conceptions of cities as vehicles for economic growth, for political change, for meeting livelihoods and basic needs, as well as larger-scale goals of resilience and sustainability.

In recent years, different models of urban environmental transition have been introduced to illustrate the connections between health hazards and environmental impacts as cities and neighborhoods develop—for example, shifts from a "sanitary city" focused on public health and basic service provision to a "sustainable city" focused on long-term planning, resource efficiency, and ecosystem services (McGranahan, 2007). The latter includes consideration of a city's use of global and local sinks for wastes that lie outside its boundaries (McGranahan, 2007; Wilson, 2012). Within these models, key variables have been identified that make cities vulnerable to climate change (e.g., extensive infrastructure networks, high-density population in exposed or other sensitive sites).

There is the opportunity to promote societal transition that enhances resiliency and adaptive capacity in the face of accelerated climate change (Gusdorf et al., 2008; Ernstson et al., 2010; Mdluli and Vogel, 2010; Tompkins et al., 2010; Pelling and Manuel-Navarrete, 2011; Pelling, 2011a). Transition in this context can take place at a broad

Table 8-3 | Urban areas: Current and indicative future climate risks. Key risks are identified based on an assessment of the literature and expert judgments by Chapter 8 authors, with the evaluation of evidence and agreement presented in supporting chapter sections. Each key risk is characterized as very low to very high. For the near-term era of committed climate change (2030–2040), projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer-term era of climate options (2080–2100), risk levels are presented for global mean temperature increases of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state.



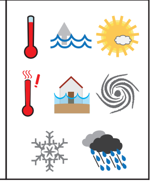
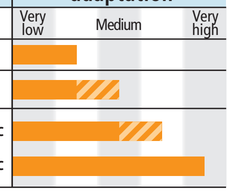
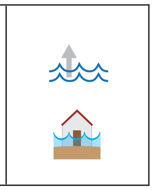
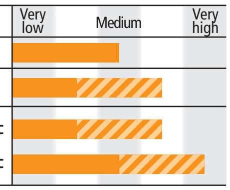
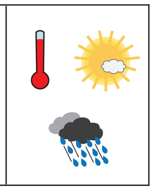
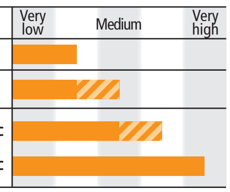
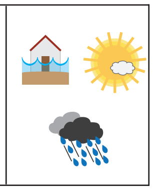
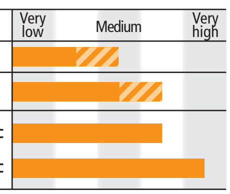
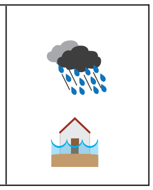
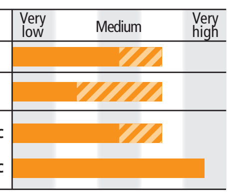
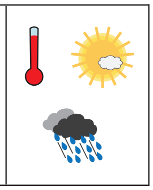
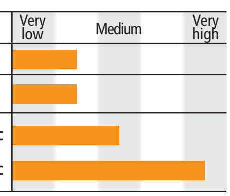
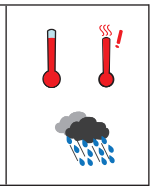
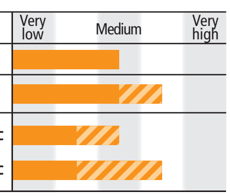
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Modal urban (*medium confidence*) [8.2, 8.3, 8.4]	Climate change will have profound impacts on urban infrastructure systems and services, the built environment, and ecosystem services and hence on urban economies and populations. This could exacerbate existing social, economic, and environmental drivers of risk, especially for vulnerable groups who lack essential services. An appropriate urban governance frame and coordinated urban adaptation focused on the built environment, improved infrastructure, and services and risk reduction has significant potential for reducing key climate risks in the medium term and especially in the long term.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Coastal zone systems (*medium confidence*) [8.2, 8.3]	Coastal cities with extensive port facilities and large-scale industries are vulnerable to increased flood exposure. High-growth cities located on low-lying coastal areas are also at greater risk. There is a possibility of nonlinear increase in coastal vulnerability over the next two decades.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Terrestrial ecosystems and ecological infrastructure (*medium confidence*) [8.2, 8.3]	Ecosystem services will be impacted by altered ecosystem functions such as temperature and precipitation regimes, evaporation, humidity, and soil moisture levels, indicating close links with sustainable water management. Knowledge gaps exist with respect to thresholds to adaptation of various ecosystems.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Water supply systems (*high confidence*) [8.2, 8.3]	Adaptation response requires changes to network infrastructure as well as demand side management, to ensure sufficient water supplies, increased capacities to manage reduced freshwater availability, flood risk reduction, and water quality.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Waste water system (*high confidence*) [8.2, 8.3, 8.4]	Managing waste water flows improves water supply and ecosystem services. Reducing vulnerability of infrastructure may be easier in new areas, well-funded local bodies, or as part of scheduled interventions.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Green built infrastructure (*medium confidence*) [8.3]	Green infrastructure not utilized sufficiently in most cities. Climate change impacts can bring attention to the dual benefits of green infrastructure for climate change mitigation and impact management.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Energy systems (*high confidence*) [8.2, 8.4]	Most urban centers are energy intensive, with energy-related climate policies focused only on mitigation measures. A few cities have adaptation initiatives underway for critical energy systems. There is great potential for non-adapted, centralized energy systems to magnify and cascade impacts to national or transboundary consequences from localized extreme events.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

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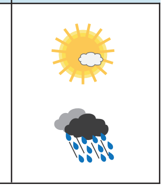
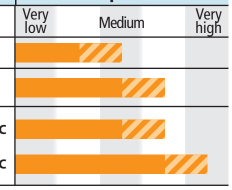
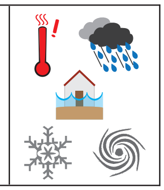
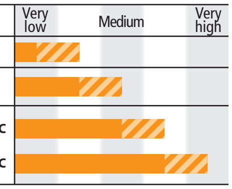
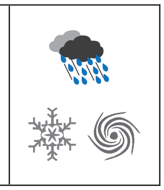
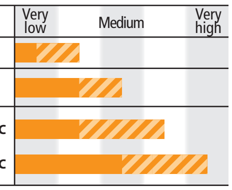
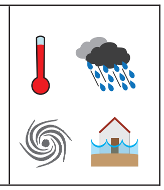
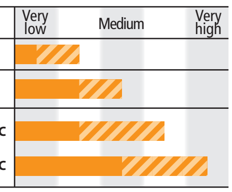
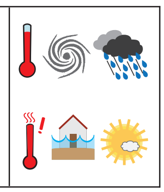
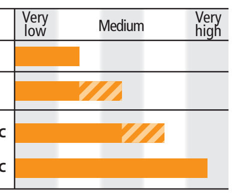
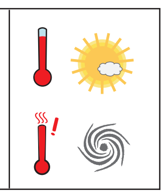
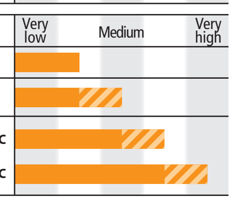
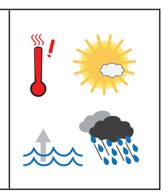
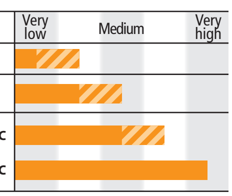
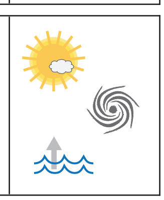
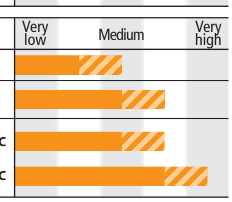
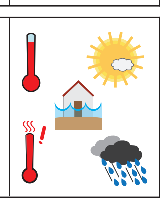
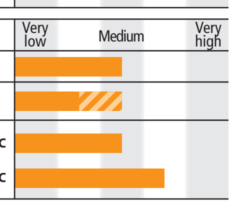
Table 8-3 (continued)

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Food systems and security (*high confidence*) [8.2, 8.3]	Urban food sources are dependent on local, regional, and often global 8.2, 8.3 supplies. Climatic drivers can exacerbate food insecurity, especially of the urban poor. Enhanced social safety nets can support adaptation measures. Urban and peri-urban agriculture, local markets, and green roofs hold good prospects as adaptive measures, but are under-utilised in rapidly growing cities.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Transportation systems (*medium confidence*) [8.2, 8.3]	A difficult sector to adapt due to large existing stock, especially in developed country cities, leading to potentially large secondary economic impacts with regional and potentially global consequences for trade and business. Emergency response requires well-functioning transport infrastructure.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Communication systems (*medium confidence*) [8.2, 8.3]	Resilient communication systems are a critical component of emergency response, and therefore adaptation. The rise of decentralized and networked mobile communications offers great potential for real-time and easily accessed information dissemination and communication systems. Information quality control is a key element in realizing the potential of communications systems for early warning and adaptation.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Urban risks associated with housing (*high confidence*) [8.3]	Poor quality, inappropriately located housing is often most vulnerable to extreme events. Adaptation options include enforcement of building regulations and upgrading. Some city studies show the potential to adapt housing and promote mitigation, adaptation, and development goals simultaneously. Rapidly growing cities, or those rebuilding after a disaster, especially have opportunities to increase resilience, but this is rarely realized. Without adaptation, risks of economic losses from extreme events are substantial in cities with high-value infrastructure and housing assets, with broader economic effects possible.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Human health (*high confidence*) [8.2, 8.3, 8.4]	Health is a higher order risk impacted by key developmental issues including water supply, water and air quality, waste management, housing quality, sanitation, food security, and provision of health care services and insurance. Certain groups of people are particularly vulnerable, such as the elderly, the chronically ill, the poor, and the very young, and require targeted social care interventions. Longer term developmental improvements need considerable financial resources and coherent intergovernmental action, limiting prospects for near-term adaptation.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Human security and emergency response (*medium confidence*) [8.3, 8.4]	Security is linked to key developmental issues such as income, housing, health care, education, and food security. Moderate prospects as city governments can enhance emergency response services, to significantly reduce vulnerability for those who are most at risk. Where security and emergency forces have limited public trust, and especially with regard to gender issues, scope for supporting adaptation and risk management is considerably constrained.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Key economic sectors and services (*medium confidence*) [8.2, 8.3]	Large diversity across cities in terms of key economic sectors and adaptive capacity to disruptions in city services. Cities reliant on climate-sensitive tourism or agriculture may require economic diversification. Good prospects for advancing co-benefits through "green" and "waste" economy.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Livelihoods (*medium confidence*) [8.3]	Informal economy is more vulnerable, and often less adaptive in the short term. Social protection measures, in the specific context of urban livelihoods, are required.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Poverty and access to basic services (*high confidence*) [8.3]	Reducing basic service deficit could reduce hazard exposure, especially of the poor and vulnerable, alongside upgrading of informal settlements, improved housing conditions and enabling the agency of low-income communities. Significant prospects where adaptation is already being implemented as part of human development or social protection.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

scale, but can also often occur with incremental changes, potentially precipitating regime level shifts (Pelling and Manuel-Navarrete, 2011). Although such shifts also can happen as a result of discrete regime failure (Pelling, 2011a), this is less common. Such transformational changes have been observed in a variety of urban disaster contexts. Most often they follow urban earthquake events (e.g., in Nicaragua, Guatemala, Turkey) but are also associated with flooding in Bangladesh (Pelling, 2011a). Disasters can enable regime level change at moments in history where competing approaches to development have political voice, an organizational base that articulates competing analysis of the causes of the disaster, and weak systemic counter response (Pelling, 2001a).

Climate change may exacerbate existing social and economic stressors in cities with the potential to affect urban livelihoods, engender political or social upheaval, or generate other negative impacts upon human security (Bunce et al., 2010; Siddiqi, 2011; Simon and Leck, 2010; see Chapters 22-30 for more detail). Climate change could potentially contribute to violent conflicts and spur migration from highly vulnerable sites in cities or increasingly environmentally stressed locales (Reuveny, 2007; Adamo, 2010; de Sherbinin et al., 2011). But there is considerable uncertainty regarding projections.

Migration may represent an important household strategy to adapt by diversifying income sources and livelihoods (Tacoli, 2009). Although climate change can significantly disrupt livelihoods, outcomes will depend on particular social structures, state institutions, and other broader determinants of human security (Barnett and Adger, 2007). In sum, "dwindling resources in an uncertain political, economic and social context are capable of generating conflict and instability, and the causal mechanisms are often indirect" between climate and conflict (Beniston, 2010, p. 567).

Different management solutions to climate change also have implications for equity (Pelling et al., 2012). For example, the privatization of urban water supply and sanitation systems can advantage specific groups over others. Conversely, community-based solutions that also build social capital can be a component in generating urban resilience. However, even these solutions may exacerbate inequality at the city level, with only those local areas with strong levels of social capital being able to benefit most from community led action or garner support from international and national partners (UN-HABITAT, 2007; Pelling et al., 2012).

Table 8-3 serves as the link between Section 8.2 (which focuses on climate change risks and impacts) and Section 8.3 (which focuses on adaptation). It summarizes key risks from climate change to urban areas and the potential to reduce risk through adaptation for the present, near term (2030–2040), and long term (2080–2100). Table 8-6 has comparable summaries of key risks and potential for adaptation for Dar es Salaam, Durban, London, and New York City. For the long term, under a global mean temperature increase of 2°C above preindustrial levels, many key risks increase from the near term. High adaptation can reduce these risk levels, although for most key risks not as much as high adaptation in the near term. For the long term under a temperature increase of 4°C above preindustrial levels, almost all key risks are "very high" and with many of them remain very high with high adaptation.

8.3. Adapting Urban Areas

8.3.1. Introduction

Since the Fourth Assessment Report, the literature on urban climate change adaptation has increased significantly, especially in three aspects:

- The examination of risks and vulnerabilities for particular cities
- The definition of "resilience" and identification of opportunities to strengthen resilience at all scales
- Documentation produced by or for particular city governments on adaptation.

There is less on local government decisions to include adaptation in plans and investment programs, but see Solecki (2012) and Roberts (2008, 2010) for exceptions. As described below, studies have also examined how to link adaptation and city development plans and adaptation measures for key sectors.

It has been suggested that "the complexities and uncertainties associated with climate change pose by far the greatest challenges that planners have ever been asked to handle" (Susskind, 2010, p. 219). Municipal and higher-level adaptation plans will need to take into account uncertainty about future climates and extremes. These will need to consider direct and indirect economic costs, including the trade-off of inaction and locking into ill-adapted infrastructure versus investment in adaptation when climate change is less than anticipated (Hallegatte et al., 2007a). Several U.S. studies have considered the cost on inaction for specific states (Niemi et al., 2009a,b,c; Repetto, 2011a,b, 2012a,b,c,d; Backus et al., 2012; Wilbanks et al., 2012).

While local governments are the fulcrum of urban adaptation planning, challenges include inadequate resources and technical capacities and a lack of data on climate-related risks and vulnerabilities. Existing climate models are not downscaled to the city level. Data on climate change risks are infrequently collected and often fragmented across city government departments (Hardoy and Pandiella, 2009). Many proposed adaptation measures respond to specific local or regional hazard risks that may not be directly climate related (Bulkeley, 2010). To encourage local dialog in adaptation planning, urban climate data need to be integrated geographically, across time scales, and consider the range of regional benefits and costs of climate policy (Ruth, 2010).

8.3.2. Development Plans and Pathways

As AR4 emphasized, many of the forces shaping greenhouse gas emissions also underlie development pathways—including the scale, nature, and location of investment in infrastructure (Wilbanks et al., 2007). These influence the form and geography of urban development as well as the scale and location of climate-related risks to urban buildings, enterprises, and populations. Local, provincial, and national governments share responsibility for encouraging new investments and migration flows away from high-risk sites through climate-sensitive disaster risk management, urban planning, and zoning and infrastructure investments. But the priority given to economic growth usually means this is rarely implemented with vigor (Douglass, 2002; Reed et al., 2013).

8.3.2.1. Adaptation and Development Planning

Urban adaptation is becoming important to some national and regional governments and many city governments. In high-income countries, interactions and division of responsibility between national and local level have been examined (see, e.g., Massetti et al., 2007, for Italy and Juhola and Westerhoff, 2011, for Italy and Finland); also local adaptation implementation through subsidies and flexible schemes in different contexts and the transfer of authority and resources to the city level (for the Netherlands; see Gupta et al., 2007). New decision making strategies for local governments consider the complexity and dynamics of evolving socio-ecological systems (Kennedy et al., 2011), for instance, adaptation plans and responses in Sydney to cope with sea level rise and storms (Hebert and Taplin, 2006) and adaptation planning in California (Bedsworth and Hanak, 2010).

The literature on urban adaptation in low- and middle-income nations has grown since AR4 (see Box 8-1 for publications since 2007). A 2011 review (Hunt and Watkiss, 2011) could draw on eight case studies in Asia, five in Africa, four in South America, as well as cases from Europe, Northern America, and Australasia.

Four issues can be highlighted around urban adaptation:

- Low- and middle-income nations have most of the world's current and future urban population.
- Key development issues of poverty and social inequality may be aggravated by climate change.
- Human agency among low-income inhabitants and organizations is important in building local responses.
- Well-functioning multilevel governance helps in developing adaptation strategies (Sánchez-Rodríguez, 2009).

Although few publications suggest specific operational strategies, they do stress the importance of the link between climate adaptation and development—urban infrastructure and other development deficits can contribute to adaptation deficits. Manuel-Navarrete et al. (2011) explore this interplay in the Mexican Caribbean, where hurricane exposure and vulnerability are influenced by political decisions and contingent development paths. Few reports exist on multidimensional approaches to operational adaptation. There are some examples of adaptation integrated with development interventions and addressing structural drivers of social and urban vulnerability—for instance, Climate Action Plans of Mexico City, Cartagena, and San Andrés de Tumaco (Sánchez-Rodríguez, 2009).

Despite growing acceptance of its importance, there are reasons for the general lack of attention to urban adaptation. First, national climate change policies usually give little attention to urban adaptation compared to sectors like agriculture. The ministries or agencies responsible for these policies often have little involvement in urban and little influence on those whose cooperation is essential, for example, for social policies, public works, and local government (Hardoy and Pandiella, 2007; Ojima, 2009; Roberts, 2010). Social policies and priorities influence the social and spatial distribution of climate-related risk and vulnerability—for instance, provision for health care, emergency services, and safety nets—yet few agencies recognize their potential role in reducing risk and vulnerability.

A second factor is the initial focus for many cities on mitigation rather than adaptation (with commitments made to lowering GHG emissions), in part because of the focus of international support. Local decision makers frequently view climate change as a marginal issue, but adaptation usually ranks lower than mitigation on the agenda (Bulkeley, 2010; Simon, 2010). Mexico City focuses on mitigation, but adaptation is still a vague concept (GDF, 2006, 2008) seen more, for instance, as a capacity to cope with floods through early warning systems than through comprehensive, long-term measures such as watershed management to reduce the speed and volume of flood waters. There is still little

Box 8-1 | Recent Literature on Urban Adaptation in Low- and Middle-Income Nations

Among the papers and books considering climate change adaptation in urban areas since 2007 are those on Cape Town (Mukheibir and Ziervogel, 2007; Ziervogel et al., 2010; Cartwright et al., 2012), Durban (Roberts, 2008, 2010; Roberts et al., 2012; Cartwright et al., 2013; Roberts and O'Donoghue, 2013), and other urban centers in Africa (Douglas et al., 2008; Wang et al., 2009; Lwasa, 2010; Kithiia and Lyth, 2011; World Bank, 2011; Adelekan, 2012; Castán Broto et al., 2013; Kiunsi, 2013; Silver et al., 2013); urban centers in Bangladesh (Alam and Rabbani, 2007; Jabeen et al., 2010; Banks et al., 2011; Haque et al., 2012; Roy et al., 2013); India (Revi, 2008; Sharma and Tomar, 2010; Saroch et al., 2011); Pakistan (Khan et al., 2008); Philippines (Button et al., 2013); and Latin America (Romero-Lankao, 2007, 2010; Hardoy and Pandiella, 2009; Hardoy and Romero-Lankao, 2011; Hardoy and Ruete, 2013; Hardoy and Velasquez Barrero, 2013; Luque et al., 2013). In China, discussions of division of responsibility between national and local levels include Teng and Gu (2007), Liu and Deng (2011), and Li (2013).

Other papers or books discussing urban adaptation in low- and middle-income nations include de Sherbinin et al. (2007), McGranahan et al. (2007), Agrawala and van Aalst (2008), Bartlett (2008), Kovats and Akhtar (2008), Ayers (2009), Bicknell et al. (2009), Tanner et al. (2009), Rosenzweig et al. (2011), Moser et al. (2010), World Bank (2010b), Manuel-Navarrete et al. (2011), Moench et al. (2011), UN-HABITAT (2011a), Bulkeley and Castan Broto (2013), and Bulkeley and Tuts (2013).

literature on adaptation for Brazilian cities (Ojima, 2009; Soares, 2009). In Sao Paulo, adaptation is limited to broad declarations about necessary actions, even as the city gets hit by floods, landslides, and water scarcity (Puppim de Oliveira, 2009; Nobre et al., 2010; Martins and da Costa Ferreira, 2011). The pressure on national and local governments to act is lessened by the scant public awareness of the importance of climate change adaptation (Nagy et al., 2007), and a "knowledge gap" between policy makers and scientists (Sánchez-Rodríguez, 2011). However, as Section 8.4 describes, interest in urban adaptation is growing, encouraged by the increasing engagement of transnational municipal networks and donor agencies (Bulkeley, 2013).

8.3.2.2. Disaster Risk Reduction and Its Contribution to Climate Change Adaptation

The growing concentration of people and activities in urban centers and the increasing number and scale of cities can generate new patterns of disaster hazard, exposure and vulnerability, as evident in the rising number of localized disasters in urban areas in many low- and middle-income nations associated with extreme weather (storms, flooding, fires, and landslides) (Douglas et al., 2008; UNISDR, 2009, 2011). This is relevant to climate change adaptation, given the increasing frequency and intensity of potentially hazardous weather events associated with climate change. Extreme weather events have also helped raise awareness of citizens and local governments of local risks and vulnerabilities.

Exposure to weather-related risk in growing urban areas increases when local governments fail to address their responsibilities by expanding or upgrading infrastructure and services and reducing risk through building standards and appropriate land use management (UNISDR, 2009, 2011). This is typical in countries with low per capita GDPs and weak local governance (i.e., in the first two categories of Table 8-2), and can be exacerbated by rapid urban population growth. Urbanization accompanied by more capable and accountable local governments can reduce disaster risk, as evident in the declines in mortality from extreme weather (and other) disasters in many middle- and all high-income nations (UNISDR, 2011). The most urbanized nations generally have the lowest mortality to these events (UNISDR, 2009).

Local government investment is usually a small proportion of total investment in and around an urban center, but has particular importance in risk reduction. Urban governments have explicit responsibilities for many assets that may be risk prone, often including schools, hospitals, clinics, water supplies, sanitation and drainage, communications, and local roads and bridges (IFRC, 2010).

Even where private provision for these assets is significant, local government usually coordinates such provision and has a significant planning and regulation role, ensuring buildings and infrastructure meet needed standards and guiding development away from high-risk areas.

From the late 1980s, some Latin American cities took a new approach to disaster risk, involving three processes:

- Detailed analyses of local disaster records, including smaller events than those in international databases
- Recognition that most disasters were the result of local failures to assess and act on risk
- Recognition of the central roles of local governments in disaster risk reduction, supported national and local civil defense organizations, working with civil society and settlements most at risk (UNISDR, 2009; IFRC, 2010).

This led to institutional and legislative changes at national or regional level (Gavidia, 2006; IFRC, 2010). In Colombia, a national law supports disaster risk reduction and a National System for Prevention and Response to Disasters, shifting the main responsibility for action to municipal administrations. In Nicaragua, the National System for Disaster Prevention, Mitigation and Response (SINAPRED) works with local government to integrate disaster mitigation and risk reduction into local development

Frequently Asked Questions

FAQ 8.1 | Do experiences with disaster risk reduction in urban areas provide useful lessons for climate-change adaptation?

There is a long experience with urban governments implementing disaster risk reduction that is underpinned by locally driven identification of key hazards, risks, and vulnerabilities to disasters and that identifies what should be done to reduce or remove disaster risk. Its importance is that it encourages local governments to act before a disaster—for instance, for risks from flooding, to reduce exposure and risk as well as being prepared for emergency responses prior to the flood (e.g., temporary evacuation from places at risk of flooding) and rapid response and building back afterwards. In some nations, national governments have set up legislative frameworks to strengthen and support local government capacities for this (Section 8.3.2.2). This is a valuable foundation for assessing and acting on climate-change related hazards, risks, and vulnerabilities, especially those linked to extreme weather. Urban governments with effective capacities for disaster risk reduction (with the needed integration of different sectors) have institutional and financial capacities that are important for adaption. But while disaster risk reduction is informed by careful analyses of existing hazards and past disasters (including return periods), climate change adaptation needs to take account of how hazards, risks, and vulnerabilities will or might change over time. Disaster risk reduction also covers disasters resulting from hazards not linked to climate or to climate change such as earthquakes.

processes (von Hesse et al., 2008; IFRC, 2010). Other initiatives in Central and South America include the influence of La Red (IFRC, 2010), the DIPECHO project "Developing Resilient Cities," and UNDP and GOAL in Central America. In growing numbers of cities in Asia (Shaw and Sharma, 2011) and Africa (Pelling and Wisner, 2009), experiences with community-driven "slum" or informal settlement upgrading has led to a recognition of its potential to reduce risk and vulnerability to extreme weather events, most effectively when supported by local government and civil defense response agencies (Boonyabancha, 2005; Archer and Boonyabancha, 2011; Carcellar et al., 2011).

The Homeless People's Federation of the Philippines developed a series of effective responses following major disasters, including community-rooted data gathering (assessing destruction and victims' immediate needs); trust and contact building; support for savings; registering community organizations; and identifying needs, including building materials loans for repairs. The effectiveness of these measures is much enhanced with local government support (Carcellar et al., 2011) and these experiences have helped inform community-based adaptation (Section 8.4).

International networks supporting innovation in disaster risk reduction and/or climate change adaptation and inter-city learning include La Red in Latin America which has been operating for 3 decades (IFRC, 2010) and the cities program of the Asian Disaster Preparedness Centre (ADPC). As donor interest has grown in supporting disaster risk management as a vehicle for climate change adaptation, a number of urban resilience programs have developed including ACCCRN (Asian Cities Climate Change Resilience Network; Brown et al., 2012), the UNISDR (United Nations International Strategy for Disaster Reduction Making Cities Resilient) network (Johnson and Blackburn, 2013), the ICLEI (Local Governments for Sustainability) city adaptation network, and UN-HABITAT's Cities and Climate Change Initiative.

Despite growing international support for urban disaster risk management, local governments have difficulty accessing the resources to make real change (von Hesse et al., 2008). Local government risk reduction investments are not seen as priorities and have to compete for scarce resources with what are judged to be more pressing needs. Effective policies are often tied to the terms of particular mayors or political parties (Mansilla et al., 2008; Hardoy et al., 2011). In most cases, risk reduction is not integrated into development plans or all relevant local government departments. Manizales, Colombia, is an exception: risk reduction has long been seen as part of local development and collective interests take precedence over party political interests (Hardoy and Velasquez Barrero, 2013).

Disaster risk management is increasingly positioned as a frontline sector for integrating climate change adaptation into everyday decision making and practices (IPCC, 2012), as seen in the plans of municipalities such as Tegucigalpa and Montevideo (Aragón-Durand, 2011). Where it is taken seriously, it offers real opportunities for synergy as the long-range nature of climate change concerns and its policy visibility can enhance local support for disaster risk management. There is considerable scope in international frameworks and national responsibilities for better coordination to make urban disaster risk management climate resilient (Aragón-Durand, 2008; IPCC, 2012).

8.3.3. Adapting Key Sectors

8.3.3.1. Adapting the Economic Base of Urban Centers

Section 8.2 described how climate change can change the comparative advantages of cities and regions—for instance, by influencing climate sensitive resources, water availability, and flooding risks. Many case studies show how extreme weather can impede economic activities, damaging industrial infrastructure and disrupting ports and supply chains (Section 8.2.3.4). Vugrin and Turnquist (2012) discuss design for resilience in distribution networks such as electric power, gas, water, food production, and manufacturing supply chains. This requires absorptive capacity (to withstand extreme weather), adaptive capacity (e.g., service provision through alternative paths), and restorative capacity (quick and cheap recovery).

When urban centers fail to adapt to risks, it may discourage new investment and lead enterprises to move or expand to safer locations. Multinational corporations and many national businesses are adept at changing location in response to changing opportunities and risks, including high insurance costs. Disasters can change perceptions of risk. Businesses may adapt to avoid impacts in their own facilities but be affected by impacts to utilities and other businesses or to their workforce and the services they use (schools, hospitals) (Hallegatte et al., 2011a; da Silva, 2012). Limited local capacity to reconstruct means increased vulnerability to future extreme events and less new investment weakens the economic base (Benson and Clay, 2004; Hallegatte et al., 2007b, 2011a). Past experience in the USA and Europe show the difficulties city governments can face in attracting new investment when a city or region's main activity weakens. If climate change forces changes to economic structure and business models, transitions may be hard to manage (Berger, 2003). Specific adaptation policies may make the transition more rapid and less painful. For instance, adaptation is generally cheaper and easier in greenfield sites—as low-risk sites are chosen, trunk infrastructure to appropriate standards is installed and building and land use regulations enforced. Retrofitting existing infrastructure and industries is generally more expensive (McGranahan et al., 2007).

Within and around urban centers, local governments may require several strategies to strengthen resilience including selective relocation, better land use planning, and revised building regulations to retrofit or flood-proof structures (Hanson et al., 2011). Synergies can be encouraged where land use management around a city supports rural livelihoods, and protects ecosystem services (Section 8.3.3.7). There may be opportunities for proactive adaptation outside larger cities where much of the future urban growth will occur. Manizales, Colombia, which has long had innovative environmental and disaster risk reduction policies has begun incorporating climate change and environmental management into its local development agenda, including the establishment of city climate monitoring systems (Hardoy and Velasquez Barrero, 2013). But most smaller urban centers are institutionally weaker and may lack the investment capacity and critical infrastructure.

Adapting the urban economic base may require short- and long-term strategies to assist vulnerable sectors and households. The consequences of climate change for urban livelihoods may be particularly profound

Frequently Asked Questions

FAQ 8.2 | As cities develop economically, do they become better adapted to climate change?

Cities and nations with successful economies can mobilize more resources for climate change adaptation. But adaptation also needs specific policies to ensure provision for good quality risk-reducing infrastructure and services that reach all of the city's population and the institutional and financial capacity to provide, and manage these and expand them when needed. Poverty reduction can also support adaptation by increasing individual, household, and community resilience to stresses and shocks for low-income groups and enhancing their capacities to adapt. This provides a foundation for building climate change resilience but additional knowledge, resources, capacity, and skills are generally required, especially to build resilience to changes beyond the ranges of what have been experienced in the past.

for low-income households who generally lack assets or insurance to help them cope with shocks (Moser and Satterthwaite, 2009). The informal sector is a significant part of the economy for most urban centers, providing employment for large numbers. But the effects of extreme weather on the informal economy are rarely considered, as in 2003 floods in Santa Fe, Argentina (Hardoy and Pandiella, 2009). In Kelurahan Pabean Pekalongan in Central Java, batik production, the primary livelihood, is being disrupted by increasingly frequent floods (UN-HABITAT, 2011b). Cash transfers and safety nets are being considered to help low-income groups cope with the short-term impacts of climate change (Sanchez and Poschen, 2009), as well as climate variability. But these will not address all the risks they face or support collective or public investments in risk-reducing infrastructure and services.

There is a growing discussion of the importance of support for a "green economy" with green infrastructure to help shift nations' economic and employment base toward lower carbon, more resilient, more sustainable patterns that respect regional and global ecological and resource limits. For urban centers, this means highlighting new (or adapted) business opportunities that limit anthropogenic climate change, resource depletion, and environmental degradation. Sometimes social inclusivity and eco-efficiency are included as mutually reinforcing principles (e.g., Allen and Clouth, 2012). The literature has begun to explore the changes needed in production systems (especially in carbon intensity, waste generation, and management), buildings, transport systems, electricity generation (including incorporating solar and wind), and consumption patterns of wealthier groups (Hammer et al., 2011; UN-HABITAT, 2012a,b,c,d; World Economic Forum, 2013). As yet, there is too little detailed discussion of how a green economy can be fostered in relation to particular cities or in regard to the incentives and regulations that can shift private investment to this.

The 'waste economy' in cities in low- and middle-income nations is important to the green economy, providing livelihoods (Hardoy et al., 2001; Hasan et al., 2002; Medina, 2007) and contributing to waste reduction and GHG emission reduction (Ayers and Huq, 2009). In Brazil's main cities, more than half a million people are engaged in waste picking and recycling (Fergutz et al., 2011), in Lima an estimated 17,000, and in Cairo 40,000 (Scheinberg et al., 2011). The ways city governments choose to work with (or ignore) those in this waste economy have obvious implications for employment and for resource use.

For some cities, there is documentation of the adaptation costs to protect or enhance the economic base. Hallegatte et al. (2013) assess present and future flood losses in the world's 136 largest coastal cities and show that the estimated costs of adaptation are far below the estimate of losses in the absence of adaptation. The paper also highlights the differences in the cities most at risk, depending on whether the ranking is by economic average annual losses or by such losses as a proportion of each city's GDP. In the first, it is mainly cities in high-income nations, in the second, mainly prosperous cities in middle-income nations.

Mombasa may have to redesign and reconstruct the city's ports, protect cement industries and oil refineries, and relocate some industries inland, all requiring major capital investments (Awuor et al., 2008). Adaptation can help protect many parts of Rio de Janeiro's diverse economy (including manufacturing, oil refineries, shipyards, and tourism) and the large populations living in informal settlements (favelas) on land at risk of landslides (de Sherbinin et al., 2007). Defenses needed to safeguard coastal industries and residential areas could threaten Rio's beach tourist industry and cause further erosion to other unprotected areas. As in most cities, making Rio's economic base more resilient to climate change means resolving such trade-offs and encouraging dialog among local stakeholders (Ruth, 2010).

As yet, there is little evidence that cities' adaptive capacities influence private sector investments. But private investment is influenced by the quality and availability of infrastructure and services that are an essential part of adaptive capacity. Many cities in Asian high growth economies are located in low-elevation coastal zones undergoing rapid urbanization and economic transformation (McGranahan et al., 2007). Cyclones are common in many of these coastal settlements. Rising concentrations of people, infrastructure, and industries along India's coasts, without adaptation, could mean nonlinear increase in vulnerability over the next 2 decades (Revi, 2008). The same is true for China (McGranahan et al., 2007). In most nations, urban governments find it difficult to prevent new developments on sites at risk of flooding, especially in locations attractive for housing or commerce, even when there are laws and regulations in place to prevent this (see Olcina Cantos et al., 2010, for an example in Alicante in Spain).

There are few economic assessments of climate change risks in West African coastal cities. Many cities or districts and their industries,

Frequently Asked Questions

FAQ 8.3 | Does climate change cause urban problems by driving migration from rural to urban areas?

The movement of rural dwellers to live and work in urban areas is mostly in response to the concentration of new investments and employment opportunities in urban areas. All high-income nations are predominantly urban and increasing urbanization levels are strongly associated with economic growth. Economic success brings an increasing proportion of GDP and of the workforce in industry and services, most of which are in urban areas. While rapid population growth in any urban center provides major challenges for its local government, the need here is to develop the capacity of local governments to manage this with climate change adaptation in mind. Rural development and adaptation that protects rural dwellers and their livelihoods and resources has high importance as stressed in particular in Chapters 9 and 13—but this will not necessarily slow migration flows to urban areas, although it will help limit rural disasters and those who move to urban areas in response to these.

infrastructure and tourism will be a challenge to protect, as in Cotonou (Dossou and Gléhouenou-Dossou, 2007), Lagos (Douglas et al., 2008), and Dakar (Wang et al., 2009).These and other important economic centers in the Gulf of Guinea (including Abidjan and Port Harcourt) have large areas close to mean sea level and highly vulnerable to erosion and rising sea levels. Rapid construction, destruction of mangrove swamps, and inadequate refuse collection compound the risks (Simon, 2010).

8.3.3.2. Adapting Food and Biomass for Urban Populations

Many urban dwellers in low- and middle-income countries suffer hunger, while a larger number face food and nutrition insecurity (Montgomery et al., 2003; Ahmed et al., 2007; Cohen and Garrett, 2010; Crush et al., 2012) owing more to their low incomes than to overall food shortages (Cohen and Garrett, 2010; Crush et al., 2012). For these low-income urban households, food expenditures generally represent more than half of total expenditures (Cohen and Garrett, 2010), putting them at particular risk from real increases in long-term food prices or temporary spikes associated with disasters.

Climate change impacts can have far-reaching influences on food security and safety, but these "will crucially depend on the future policy environment for the poor" (Schmidhuber and Tubiello, 2007, p. 708; see also Douglas, 2009). Agriculture has managed to keep up with rising demands worldwide, despite rapid population growth, the reduction in agricultural workers that accompanies urbanization, and dietary shifts that are more carbon and often land intensive (Satterthwaite et al., 2010). But food security may be eroded by competing pressures for water or bio-fuels. In addition, there may be tensions between managing land use to reduce flood risk and food and energy policies (Wilby and Keenan, 2012). Adapting urban food systems represents a major challenge and will necessitate radical changes in food production, storage, and processing (and in reducing waste), in transport/the supply chain, and in access (Godfray et al., 2010). Both supply and demand side constraints must be considered. Climate change-related constraints on agricultural production affect urban consumers through reduced supplies or higher prices; falling production and farmer incomes reduces their demand for urban goods and services; disruption to urban centers can mean disruption to the markets, services, or remittance flows on which agricultural producers rely (Tacoli, 2003). Thus, strengthening urban food security needs to take account of complex rural-urban linkages (Revi, 2008) and responses must bridge rural and urban boundaries.

Urban centers that are seriously impacted by extreme weather face serious challenges in ensuring that those affected have access to adequate and safe food and water supplies. Flooding, drought, or other extreme events often lead to food price shocks in cities (Bartlett, 2008) as well as spoiling or destroying food supplies for many households. After the 2004 floods in Bangladesh, Dhaka's rice prices increased by 30% and vegetable prices more than doubled, with urban slum dwellers and rural landless poor the worst affected (Douglas, 2009). When facing increased food prices, the urban poor adopt a range of strategies such as reduced consumption, fewer meals, purchasing less nutritious foods, or increasing income earning work hours, particularly for women and children (Cohen and Garrett, 2010). But these erode nutrition and health status, especially of the most vulnerable and fail to strengthen resilience, particularly in the context of more frequent disasters.

Adaptive local responses include support for urban and peri-urban agriculture, green roofs, local markets, and enhanced safety nets. Food price increases may be moderated by improving the efficiency of urban markets, promoting farmers' markets, and investing in infrastructure and production technologies (Cohen and Garrett, 2010). Food security may be enhanced by support for urban agriculture and street food vendors (Cohen and Garrett, 2010; Lee-Smith, 2010) and access to cheaper food or measures such as cash transfers (e.g., Brazil's Bolsa Familia Programme) or, for older groups, pensions (Soares et al., 2010). Initially rural in focus, cash transfer programs have expanded in urban areas, in some places reaching much of the low-income population (Johannsen et al., 2009; Niño-Zarazúa, 2010; Mitlin and Satterthwaite, 2013).

8.3.3.3. Adapting Housing and Urban Settlements

The built environment in urban areas has to adapt to the range of climate change impacts outlined in Section 8.2, in order to protect urban populations and economies and protect among society's most valuable assets. Knowledge and innovation are required for adapting existing and new buildings. This will be built on the bedrock of affordable housing appropriate for health and safety, built to climate-resilient standards and with the structural integrity to protect its occupants long term against extreme weather (UNISDR, 2009, 2011). The resilience of poor quality housing, often at risk from extreme weather, can be enhanced via structural retrofitting, interventions that reduce risks (for instance, expanding drainage capacity to limit or remove flood risks), and non-structural interventions (including insurance). Attention to all three is more urgent where housing quality is low, where settlements are on high-risk sites, and in cities where climate change impacts are greatest. Enhancing the resilience of buildings that house low-income groups will usually be expensive and may face political challenges (Roaf et al., 2009).The range of actors in the housing sector, the myriad connections to other sectors and the need to promote mitigation and adaptation, as well as development goals, point to the importance of well-coordinated strategies that can support resilience (Maller and Strengers, 2011).

There have been studies in increasing numbers of cities to identify measures to adapt housing (and other buildings) and discussions on revising standards, although it is difficult to set standards with uncertain forecasts and scenarios and evolving risks (Engineers Canada, 2008). There is less evidence of the action plans, budget commitments, and regulation changes to implement them. Measures identified in a Bangkok assessment included flood-proofing homes, building elevated basements, and moving power-supply boxes upstairs, along with keeping enough food, water, fuel, and other supplies for 72 hours; it also pointed to regulatory changes to bolster resilience including land use restrictions in floodplains and other at-risk sites and revised safety and fire codes for buildings and other structures (BMA, GLF, and UNEP, 2009). Cape Town's climate change framework (2006) proposed housing interventions including regulations for building informal housing, in part to reduce the need for emergency response and anticipate projected climate change. Regulations in New York and Boston are being updated to address climate-related risks (City of Boston, 2011; City of New York, 2011). London and Melbourne's adaptation plans both consider strategies combining green infrastructure and housing interventions (GLA, 2010; UN-HABITAT, 2011a).

8.3.3.3.1. Housing and other buildings and extreme heat

More attention is being paid to extreme heat in particular cities (e.g., City of Chicago 2008, 2010; City of Toronto, 2013; Tomlinson et al.,2011, for Birmingham; Matzarakis and Endler, 2010, for Freiberg; GLA, 2010, for London; and Giguère, 2009, for Quebec), also in regard to low-income housing in Athens (see Sakka et al., 2012).

Attention is required to buildings that provide protection from hot days and to populations more vulnerable to extreme heat, including those who work outside (see Box CC-HS). In locations with large daily variations in temperature, the response can include upgrading homes with limited ventilation and low thermal mass. Chicago's 2008 Climate Action Plan discussed the need for innovative cooling ideas for property owners (City of Chicago, 2008, p. 52). Air conditioning and other forms of mechanical cooling are too expensive, unavailable for the many urban households with no electricity, and maladaptive when electricity generation contributes to GHG emissions. Residents' vulnerabilities may be exacerbated if electricity supplies are unreliable; blackouts tend to occur on the hottest days when demand is highest (Maller and Strengers, 2011, p. 3). The literature on adaptations for extreme heat focuses on high-income nations and more attention is required to this in urban centers in low- and middle-income nations.

Passive cooling can be used in both new-build and retrofitted structures to reduce solar and internal heat gains, while enhancing natural ventilation or improving insulation (Hacker and Holmes, 2007; Roberts, 2008a,b). Passive designs, using super-insulation, ventilation, and other measures to ensure energy is not required for most of the year, as in the Beddington Zero Energy Development (BedZED) in London (Chance, 2009) or Germany's Passive Haus standard (Rees, 2009), have set precedents for mitigating household emissions but they can simultaneously contribute to adaptation. Thermal mass can be used for cooling, "because it introduces a time-delay between changes in the outside temperature and the building's thermal response necessary to deal with the high daytime temperatures" (Hacker and Holmes, 2007, p. 103). Structures in southern Europe already use solar shading, ventilation, and thermal mass to promote enhanced cooling (Hacker and Holmes, 2007). Simulations for London (under UKCIP02 Medium-High emissions scenarios) suggest that passive designs are an "eminently viable option for the UK, at least over the next 50 years or so" (Hacker and Holmes, 2007, p. 111). There are several obstacles though: opening windows may be hampered by security concerns or noise pollution (Hacker and Holmes, 2007). Modern windows may not ventilate well, and site restrictions and cost can impede the use of passive cooling in refurbishing existing buildings (Roberts, 2008a).

8.3.3.3.2. Housing and disaster-preparedness measures

When populations are displaced or temporarily evacuated, provision for emergency shelters and services have to be able to respond, especially for vulnerable residents. For instance, after Cyclone Larry in Queensland (in 2006) and New South Wales' coastal flooding (in 2007), officials recalled the strains faced in shelters and the coordination difficulties with emergency health workers, police, insurance, and other agencies (Jacobs and Williams, 2011). This points to the range of social support, structural strategies, and interagency efforts that local authorities may develop to adapt to climate change. For many urban centers, there is also the issue of how to move populations at risk, which presents many challenges (Roaf et al., 2009).

Urban centers facing extreme heat require plans that provide early warning for citizens, inform them of measures they can take and ensure adequate water provision, back up electricity, emergency health care, and other public services focused on vulnerable residents, especially infants and the elderly in hospitals and residential facilities (Brown and Walker, 2008; Hajat et al., 2010) or living alone. Public buildings with cooling may also be required. Cities with responses to hot days for those most at risk are mainly from high-income nations. Several hundred million urban dwellers in low- and middle-income nations have no access to electricity (Johansson et al., 2012) or mechanical devices that help with cooling.

8.3.3.4. Adapting Urban Water, Storm, and Waste Systems

It is challenging to summarize key adaptation strategies from the highly heterogeneous mix of urban areas across the globe. In high-income and some middle-income nations, virtually all the urban population is served by drinking quality water piped to the home 24 hours a day, by systems of sanitation that minimize risks of fecal contamination and by storm and surface drainage. Many urban centers in such nations may face serious climate change-related challenges for water, but do not have to address the fact that much of their population lacks piped water, toilets, or storm drains. They can also bill users for much of the funds required for water provision and management.

At the other extreme are a very large number of urban centers with large deficits in provision for water, sanitation, and drainage and with weak, under-resourced institutions (UN-HABITAT, 2003b; UNEP, 2012). Around a billion people live in informal settlements where providers responsible for water and sanitation are often unwilling to invest or not allowed to do so (Mitlin and Satterthwaite, 2013). New York City can develop a plan to ensure adequate water supplies costing billions of dollars (Solecki, 2012); many cities in sub-Saharan Africa have not only very large deficits in piped water, sewers, and drains but also very limited investment capacities (see, e.g., Kiunsi, 2013, for Dar es Salaam).

Some studies have sought to estimate the costs of adapting urban water and sanitation systems, pointing to the need for significant investments (Arnell, 2009). Muller (2007) suggests that US$1 to 2.7 billion is required annually in sub-Saharan African cities to adapt existing water infrastructure; this does not include the cost of addressing deficient infrastructure. Another US$1 to 2.6 billion a year is required to adapt new developments (including water storage, waste water treatment, and electricity generation).

8.3.3.4.1. Adapting urban water supply systems

For cities with climate change adaptation plans, water and waste water management are usually important components (see, e.g., Helsinki Region Environmental Services Authority, 2012). Major et al. (2011) list a range of cities that have begun to adapt water systems and other infrastructure including Boston, London, Halifax (Canada), New York, Seattle, and Toronto. The U.S. government has developed a guide for adaptation strategies for water utilities (EPA, 2013). But developing such measures is not yet commonplace.

Supply-side approaches to seasonal water shortages are frequently advocated. An analysis of 21 draft Water Resources Management Plans in the UK found that agencies usually favored reservoirs and other supply-side measures to adapt to climate change, although authors suggest that demand-side interventions may also be needed (Charlton and Arnell, 2011). To expand its reservoir capacity after 1998 floods exposed existing infrastructure, Rotterdam developed plans combining adaptation and urban renewal goals, mixing economic activities with water-based adaptive designs, including "water retention squares" and green roofs, floating houses, and networks of channels (Van der Brugge and De Graaf, 2010). Seattle has used demand-side strategies to cut water consumption including aggressive conservation measures, system savings, and price increases (Vano et al., 2010).

In Mexico City, a number of measures in the water sector have been proposed many times since the 1950s but not acted on, including a decrease in water use and the restoration and management of urban and rural micro-basins (Romero-Lankao, 2010). Adaptation measures have been conceived as too general and lacking institutional commitment. In Durban, where the water sector is revenue earning and seen as critical to development, the importance of climate change adaptation was recognized as a priority (Roberts, 2010). In Cape Town, which faces profound challenges in ensuring future supplies, water management studies identified the need to consider climate change and population and economic growth (Mukheibir and Ziervogel, 2007). During the 2005 drought, the local authority substantially increased water tariffs, considered a most effective way to promote efficient water usage (Mukheibir, 2008). Other measures may include water restrictions, reuse of gray water, consumer education, or technological solutions such as low-flow systems or dual flush toilets (Mukheibir and Ziervogel, 2007).

In Phoenix, Arizona, a rapidly expanding desert city projected to reach 11 million people by 2050, most peripheral growth depends on groundwater (Bolin et al., 2010). Simulations explored how water usage may be reduced to achieve safe yield while accommodating future growth. Reducing current high use may be achieved through urban densification, increased water prices, and water conservation measures (Bolin et al., 2010). Gober et al. (2010) agree that stringent demand and supply policies can forestall "even the worst climate conditions and accommodate future population growth, but would require dramatic changes to the Phoenix water supply system" (Gober et al., 2010, p. 370). Here and in other cities in Arizona, supply-side management including active management of groundwater and groundwater storage is combined with extensive demand side measures (Colby and Jacobs, 2007).

In Quito, where reduced freshwater supplies are projected with glacier retreat and other climate-related changes, local government has formulated a range of adaptation plans, including encouraging a culture of rational water use, reducing water losses, and developing mechanisms to reduce water conflicts (Hardoy and Pandiella, 2009). However, community participation in planning and implementation has not been considered (Hardoy and Pandiella, 2009). Participatory water planning has occurred elsewhere in Latin America: stakeholders in Hermosillo, Mexico, identified and prioritized specific adaptations such as rainwater harvesting and water-saving technologies (Eakin et al., 2007).

Several cities actively encourage rainwater harvesting while others are considering its potential. Since 2004, in New South Wales, Australia, homeowners have been required to ensure that newly built houses use 40% less potable water than an established benchmark level of consumption, through water-saving measures such as water-efficient shower heads, dual-flush toilets, rainwater tanks and grey water treatment systems (Warner, 2009). Many low-income Caribbean households rely on rainwater collection systems for domestic use. Extending existing communal collection and distribution systems would require community financing or governmental interventions, as well as overcoming resistance from higher-income residents (Cashman et al., 2010). Rainwater harvesting has been promoted in several cities in India (Shaban and Sharma, 2007).

8.3.3.4.2. Waste and storm water management

More attention has been given to adaptations to help ensure sufficient water supplies than to increasing the capacity of sewer and drainage systems, or adapting them to allow for the impacts of heavier rainfall or sea level rise. We noted earlier the very large deficiencies in provision for drainage for urban centers in low- and many middle-income nations.

In St. Maarten, Netherlands Antilles, the government (after a storm water modeling study) is developing a flood warning system and considering such institutional adaptations as a new decision-support framework, centralized geographic information system (GIS) for infrastructure planning and public education, along with structural measures such as draining areas with a high groundwater table (Vojinovic and Van Teeffelen, 2007). City management in Toronto, Canada, has prioritized an upgrade of storm water and wastewater systems (Kessler, 2011). Deak and Bucht (2011) analyze past hydrological structures in Lund, Sweden, and use the concept of indigenous blue infrastructure to question current storm water management in the urban core. Cities in California have a range of flood management methods but Hanak and Lund (2012) suggest that they will also require forward-looking reservoir operation planning and floodplain mapping, less restrictive rules for raising local funds, and improved public information on flood risks. Willems and Arnbjerg-Nielsen (2013) suggest that climate change adaptation for urban drainage systems requires a reevaluation of the technical solutions implemented over the last 150 years. The objective is cities that interact with water (including storms) in a healthy, environmentally friendly, and cost-efficient way. This includes the incorporation of roads and parks into the active drainage system and the use of blue and green storm water infrastructure (Section 3.3.3.7). These authors also note that this implies changing roles for water scientists, water managers, and water engineers as well as for water users, property owners, insurers, city planners, and politicians (Willems and Arnbjerg-Nielsen, 2013; see also Willems et al., 2012). Many governments in the last 20 years have developed integrated water resource management (UNEP, 2012) with linkages between provisions for water, sanitation, and drainage and other sectors, and a recognition of the need to work with a range of partners, consider broader development goals, identify tensions or trade-offs (Willems and Arnbjerg-Nielsen, 2013), and implement low-regret anticipatory solutions. For cities, this often includes management of groundwater use and water catchment in areas outside their jurisdiction and thus collaboration with other local governments (WMO, 2008). Most examples of this are in high-income nations (for an exception, see Bhat et al., 2013).

Urban water systems usually depend on reliable electricity supplies and can be energy intensive—for instance, in conveying or treating water from distant or low-quality sources. Integrated planning (e.g., in concert with energy conservation, water catchment management and green infrastructure strategies) can minimize conflicts, support local industries, and ensure equitable access to water in cities.

8.3.3.5. Adapting Electric Power and Energy Systems

The heavy dependence of urban economies, infrastructure, services, and residents on electricity and fossil fuels means far-reaching consequences if supplies are disrupted or unreliable (Section 8.2.4.2). With mitigation concerns dominating the literature and urban energy policy discussions, there is less focus on adaptation issues (Carmin et al., 2009; Mdluli and Vogel, 2010). The UNFCCC's estimates for investment to address climate change (UNFCCC, 2007) did not include the costs of adapting the energy sector (Fankhauser, 2010). Key issues relating to energy sector adaptation, including generation and distribution, are usually national or regional and are discussed in Chapter 10. But urban governments' and residents' responses are also important. Research has suggested that "private autonomous measures will dominate the adaptation response as people adjust their buildings, [or] change space-cooling and -heating preferences…" (Hammer et al., 2011, p. 27). A few cities have adaptation initiatives underway for energy systems; others have begun to consider the steps needed (Hammer et al., 2011). Some relevant local urban concerns are the extent of the need for autonomous provision or back-up generating capacity, and the functioning of emergency services when energy supplies are disrupted or unreliable. The interrelations between energy and other sectors suggest the need for an integrated approach in understanding vulnerability and shaping appropriate responses (Gasper et al., 2011).

Despite growing concern about the potential impact of climate change and extreme weather events for the oil industry in Canada, USA, and Mexico and how hurricanes, floods, and sea level rise will disrupt oil, gas, and petrochemical installations (Levina et al., 2007; Savonis et al., 2008), few adaptation studies have been undertaken.

8.3.3.6. Adapting Transport and Telecommunications Systems

Urban centers depend on transport and telecommunications systems for daily functioning and for vital regional, national, and international supply chains. For instance, 80% of the food consumed in London is imported (Best Foot Forward, 2002). The Great Lakes–St. Lawrence route in the USA supports 60,000 jobs and US$3 billion worth of annual movement of goods (Ruth, 2010). Most large and successful cities have also spread spatially, and well-functioning transport systems support the decentralization of the workforce and businesses. Many cities, for instance, depend on underground electric rail systems which require protection from the considerable risk from flooding, such as New York and London (Eichhorst, 2009). Adapting all these systems to the impacts of climate change (including hot days, storms, and sea level rise) poses many challenges (Mehrotra et al., 2011b).

8.3.3.6.1. Transport systems

Four different aspects to adaptation strategies for transport can be highlighted: maintain and manage; strengthen and protect; enhance redundancy; and, where needed, relocation. Cities that have developed adaptation plans usually include attention to more resilient transport systems (UN-HABITAT, 2011a). Melbourne's adaptation plan notes that intense storms and wind may lead to blocked roads and disrupt traffic lights, trains, and trams and that these disruptions can be exacerbated by such compounding factors as power disruptions and emergency situations (City of Melbourne, 2009). Adaptation will require transport planners to take a whole-of-life approach to managing infrastructure, and constantly update risk assessments (Love et al., 2010). Coordination at national, regional, and local levels is important for implementing adaptation strategies in the transport sector, as climate change impacts are widespread and extend across scales (Regmi and Hanaoka, 2011). Interdisciplinary approaches can include changing meteorological hazards as well as social and political values and the governance framework for more resilient transport systems (Jaroszweski et al., 2010).

8.3.3.6.2. Adapting roads

Climate change may increase the costs of maintaining and repairing road transport networks (see Hayhoe et al., 2010, for discussion of changing conditions in Chicago). In Durban, revised road construction standards may be needed (Roberts, 2008). Coastal road adaptation may require strengthening barriers and designing roads or realigning them to higher locations to cope with sea level rise (Regmi and Hanaoka, 2011).

Transport planners are beginning to reassess maintenance costs and traditional materials—for instance, stiffer binding materials to cope with rising temperatures and softer bitumen for colder regions (Regmi and Hanaoka, 2011). But cost considerations may impede their use. The Chicago Department of Transportation decided not to use more permeable, adaptive road materials because of higher cost, although costs may fall with greater economies of scale as demand rises for such materials (Hayhoe et al., 2010). Road maintenance costs vary widely, depending on local context, and future climate scenarios. In Hamilton, New Zealand, increases in rainfall in spring (within one scenario) or winter (in another) would increase road repair costs while decreases in rainfall in other seasons could decrease them; results depend upon the scenario and further investigation was recommended (Jollands et al., 2007).

8.3.3.6.3. Adapting surface and underground railways

Underground transport systems are specific to cities and of great importance to the functioning of many major cities. They may have "particular vulnerabilities related to extreme events, with uniquely fashioned adaptation responses" (Hunt and Watkiss, 2011, p. 14). Heat impacts are often significant, as these systems gradually warm due to engine heat, braking systems, and increased passenger loads. To cope with increasing frequency of hot days, substantial investments in ventilation or cooling may be necessary (Love et al., 2010). For New York City's subways, the system's age, fragmented ownership, overcapacity, and in some cases floodplain location may augment the challenge of adaptation (Zimmerman and Faris, 2010, pp. 69-70). Storm surge flooding from Hurricane Sandy flooded eight under-river subway tunnels, severely impacting mobility and economic activity (Blake et al., 2012).

Rail systems that struggle to cope with existing climate variability may require considerable investment to withstand higher temperatures and more extreme events (see Baker et al., 2010). Railway systems may be more vulnerable to climate variability than the road system, which can more easily redirect traffic (Lindgren et al., 2009). The costs of delays and lost trips due to extreme weather events, analyzed in Boston (Kirshen et al., 2008) and Portland (Chang et al., 2010) were found to be small relative to the damage to infrastructure and other property. Floodplain restoration, use of porous pavements, and detention ponds may help address the projected increased flooding in Portland (Chang et al., 2010).

In flood-prone cities, transport systems may require more stringent construction standards, design parameters, or relocation. Much of central Mumbai is built on landfill areas and prone to flooding, but they contain the main train stations and train lines as well as large populations and a large part of the city's economy. Rising sea levels may cause shifts at the sub-surface level of landfill areas and structural instabilities (de Sherbinin et al., 2007).

8.3.3.6.4. Ports

Section 8.2 outlined the many ways in which ports can be impacted by climate change and the investments required to take account of these. Many ports remain largely unaware of the potential threats of climate change, or are slow to consider appropriate adaptation measures (Becker et al., 2012). Rotterdam's Climate Proof Programme includes as key components flood safety and accessibility for ships and passengers (Rotterdam Climate Initiative, 2010; Vellinga and De Jong, 2012). A climate risk study for the Port of Muelles el Bosque (Cartagena, Colombia) analyzed projected changes in sea level rise, storm surge height, precipitation, temperature, and wind patterns and their direct and indirect effects on port assets and operations, surrounding environment and communities, and on the trade of goods transported through the port and this helped catalyze adaptation investments (Stenek et al., 2011).

There are also the deficits in basic infrastructure noted in Section 8.2 that inhibit adaptation including the lack of all-weather roads and paths in informal settlements that constrain rapid evacuation and limit access for emergency vehicles.

8.3.3.6.5. Telecommunications

A wide range of components and sub-systems for telecommunications systems that are within cities may need adaptation to the impacts of climate change, including telephone poles and exchanges, cables, mobile telephone masts and data centers (Engineering the Future, 2011; Chapman et al., 2013).

8.3.3.7. Green Infrastructure and Ecosystem Services within Urban Adaptation

Ecosystem based adaptation has relevance for many chapters (see Box CC-EA). Ecosystem-based adaptation in urban areas as part of the climate change adaptation strategy seeks to move beyond a focus on street trees and parks to a more detailed understanding of the ecology of indigenous ecosystems, and how biodiversity and ecosystem services can reduce the vulnerability of ecosystems and people. Strategies to achieve biodiversity goals (developing corridors for species migration, enlarging core conservation areas, identifying areas for improved matrix

Box 8-2 | Ecosystem-Based Adaptation in Durban

Durban has adopted an ecosystem-based adaptation approach as part of its climate adaptation strategy. This required a series of steps (Roberts et al., 2012):

- A better understanding of the impacts of climate change on local biodiversity and the management Durban's open space. The projected warmer and wetter conditions seem to favor invasive and woody plant species.
- Improved local research capacity that includes generating relevant local data.
- Reducing the vulnerability of indigenous ecosystems as a short-term precautionary measure.
- Enhancing protected areas owned by local government and developing land use management interventions and agreements to protect privately owned land areas critical to biodiversity and ecosystem services. This can be supported by government incentives and regulation to stop development on environmentally sensitive properties, the removal of perverse incentives, and support for affected landowners.
- The promotion of local initiatives that contribute jobs and promote skills and environmental education within ecosystem management and restoration programs. Durban has initiated a large-scale Community Reforestation Programme where community level "tree-preneurs" produce indigenous seedlings and help plant and manage the restored forest areas as part of a larger strategy to enhance biodiversity refuges and water quality, river flow regulation, flood mitigation, sediment control, and improved visual amenity. Advantages include employment creation, improved food security, and educational opportunities.

management to enhance ecological viability) can have adaptation co-benefits. Recognizing that the adaptation deficit is both in the lack of conventional infrastructure and the loss of ecological infrastructure, the approach includes an interest in how ecosystem restoration and conservation can contribute to food security, urban development, water purification, waste water treatment, climate change adaptation, and mitigation (Roberts et al., 2012). The growing attention to ecosystem services includes adaptations in urban, peri-urban, and rural areas that use opportunities for the management, conservation, and restoration of ecosystems to provide services and increase resilience to climate extremes. They can also deliver co-benefits (e.g., purifying water, absorbing runoff for flood control, cleansing air, moderating temperature, and preventing coastal erosion) while helping contribute to food security and carbon sequestration (Newman, 2010; Foster et al., 2011b; GLA, 2011; Roberts et al., 2012; see also Institute for Sustainable Communities, 2010; City of New York, 2011; Oliveira et al., 2011; Tallis et al., 2011; Wilson et al., 2011; Helsinki Region Environmental Services Authority, 2012). These approaches are particularly important in low- and many middle-income countries where livelihoods for some urban residents and much of the peri-urban population depend on natural resources. But there are considerable knowledge gaps in determining the limits or thresholds to adaptation of various ecosystems and where and how ecosystem-based adaptation is best integrated with other adaptation measures. There is also some indication that the costs of ecosystem-based adaptation in urban contexts might be higher than expected, in large part because costs are higher for land acquisition and ecosystem management (Roberts et al., 2012; Cartwright et al., 2013).

Box 8-2 describes how ecosystem-based adaptation is being developed in Durban. Another example is addressing flood risk through catchment management that includes community-based partnerships supported by full cost accounting and payment for ecosystem services—rather than the more conventional canalization of rivers (Kithiia and Lyth, 2011; Roberts et al., 2012).

Although much of the early innovation in ecosystem services and green infrastructure was geared to address water shortages or flooding, its importance for climate change adaptation is increasingly recognized.

Green spaces in cities are beneficial for absorbing rainfall and moderating high temperatures. Urban forests and trees can provide shading, evaporative cooling and rainwater interception, and storage and infiltration services for cities (Pramova et al., 2012). Increasing tree cover is proposed as a way to reduce UHI. Cooling effects are especially high in large parks or areas of woodland but the land these are on face competition from developers, as well as management challenges (Pramova et al., 2012). The rapid and often unregulated expansion of cities in low- and middle-income nations may also have left a much lower proportion of the urbanized area as parks and other green spaces.

There is also lack of detailed knowledge on the climatic effects of specific urban plants and vegetation structures (Mathey et al., 2011) and on other important aspects such as the influence of green areas in local circulation patterns and impact on urban fluxes and urban metabolism (Chrysoulakis et al., 2013). In addition, green infrastructure projects may select plant material for particular purposes that do not support habitat values or large ecosystem function and greater ecosystem services.

Some city governments have focused on green infrastructure within built up areas. In the USA, Portland and Philadelphia have encouraged green roofs, porous pavements, and disconnection of downspouts to reduce storm water at much lower cost than increasing storm water storage capacity (Foster et al., 2011b). Some cities have invested in green infrastructure linked to both regeneration and climate change adaptation. The Green Grid for East London seeks to create "a network of interlinked, multi-purpose open spaces" to support the wider regeneration of the sub-region, enhancing the potential of existing and new green spaces to connect people and places, absorb and store water, cool the vicinity, and provide a mosaic of habitats for wildlife (GLA, 2008, p. 80). New York has a well-established program to protect and enhance its water supply through watershed protection. This includes city ownership of crucial land outside the city and working with land owners and communities to balance protection of drinking water with facilitating local economic development and improving waste water treatment. There is also an ambitious green infrastructure plan within the city, including porous pavements and streets, green and blue roofs, and other measures to control storm water. The program is costly, compared to constructing and operating a filtration plant, but is the most cost-effective choice for New York (Bloomberg and Holloway, 2010; Foster et al., 2011b).

The coastal city of Quy Nhon in Vietnam is reducing flood risks by restoring a 150-hectare zone of mangroves (Brown et al., 2012). Singapore has used several anticipatory plans and projects to enhance green infrastructure including its Streetscape Greenery Master Plan, constructed wetlands or drains, and community gardens (Newman, 2010). Authorities in England and the Netherlands are recognizing the linkages between spatial planning and biodiversity, but without much direct response to climate change adaptation. Barriers to action include short-term planning horizons, uncertainty of climate change impacts, and problems of creating habitats due to inadequate resources, ecological challenges, or limited authority, and data (Wilson and Piper, 2008).

In Mombasa, the Bamburi Cement Company rehabilitated 220 hectares of quarry land (Kithiia and Lyth, 2011). The resulting Haller Park attracts more than 150,000 visitors per year, and has the potential to create adaptation co-benefits. Cape Town has initiated community partnerships to conserve biodiversity, including the Cape Flats Nature project with the para-statal South African National Biodiversity Institute. Participating schools and organizations explore ecosystem services (such as flood mitigation and wetland restoration), and the project facilitates "champion forums" to support conservation efforts (Ernstson et al., 2010, p. 539).

Dedicated green areas within urban environments compete for space with other city-based needs and developer priorities. The role of strategic urban planning in mediating among competing demands is potentially useful for the governance of adaptation as demonstrated in London, Toronto, and Rotterdam (Mees and Driessen, 2011). The experience in Durban (see Box 8-2) also faces many challenges (Roberts et al., 2012), including an assumption that ecosystem-based adaptation is an easy alternative to the constraints that limit the implementation and effectiveness of "hard engineering" solutions (Roberts et al., 2012; Kithiia and Lyth, 2011). Experience in Durban shows that implementing an ecologically functional and well-managed, diverse network of bio-infrastructure requires data collection, expertise, and resources, and to have direct and immediate co-benefits for local communities and ensure integration across institutional and political boundaries. There are substantial knowledge gaps such as determining where the limits or thresholds lie; many ecosystems have been degraded to the point where their capacity to provide useful services may be drastically reduced (TEEB, 2010).

The review by Burley et al. (2012) of the wetlands of South East Queensland, Australia, indicates that adaptations focused on wetland and biodiversity conservation may impact urban form in coastal areas. A study of changes in tree species composition, diversity, and distribution across old and newly established urban parks in Bangalore, India, aims to find ways to increase ecological benefits from these biodiversity hotspots (Nagendra and Gopal, 2011). When Leipzig applied a new approach to evaluating the impacts on local climate of current land uses and proposed planning policies, using evapotranspiration and land surface emissivity as indicators, green areas and water surfaces were found to have cooling effects, as expected, but some policies increased local temperatures (Schwarz et al., 2011).

Some aspects of mitigating climate change in urban areas requires a dense urban form to maximize agglomeration economies in more efficient resource use and waste reduction and to reduce urban expansion, reliance on motorized transport, and building energy use. But adaptation may require an urban form that favors green infrastructure and open space for storm water management, species migration, and urban cooling (Hamin and Gurran, 2009; Mees and Driessen, 2011). Higher densities can prevent the maintenance of ecologically viable systems with high biodiversity and exacerbate the urban heat island, in turn generating the need for more cooling, increasing energy use, and further escalating the urban heat island effect. This is the "density conundrum" (Hamin and Gurran, 2009, p. 242): At what point are densities too high to maintain ecologically viable systems with high biodiversity, especially given that urbanization has already compromised the ability of ecosystems to buffer urban development from hazards? This situation will be further exacerbated by new hazards (e.g., floods, fires) to which systems are or will be exposed as the result of climate change (Depietri et al., 2012).

8.3.3.7.1. Green and white roofs

Green and white roofs, introduced in a range of cities, have the potential to create synergies between mitigation and adaptation. Rooftop vegetation helps decrease solar heat gain while cooling the air above the building (Gill et al., 2007), thus improving the building's energy performance (Mees and Driessen, 2011; Parizotto and Lamberts, 2011). It can reduce cooling demand and often the use of air conditioning with its local contribution to heat gain and its implications for GHG emissions (Jo et al., 2010; Zinzi and Agnoli, 2012). Rooftop vegetation can also retain water during storms, reducing stormwater runoff (Voyde et al., 2010; Palla et al., 2011; Schroll et al., 2011) and promoting local biodiversity and food production. Studies have compared the performance of living roofs across different plant cover types, levels of soil water, and climatic conditions (see, e.g., Simmons et al., 2008; Jim, 2012). Hodo-Abalo et al. (2012) confirm that a dense foliage green roof has a greater cooling effect on buildings in Togolese hot-humid climate conditions. Several field experiments combined with simulated modeling of impacts in the USA also confirm the positive thermal behavior of green roofs compared to alternative roof coverings (e.g., Getter et al., 2011; Scherba et al., 2011; Susca et al., 2011). Durban has a pilot green roof project on a municipal building; indigenous plants are being identified for the project and rooftop food production is being investigated (Roberts, 2010). New York's lack of space for street-level planting helped encourage the adoption of living roofs (Corburn, 2009). Under its Skyrise Greenery project, Singapore has provided subsidies and handbooks for rooftop and wall greening initiatives (Newman, 2010). Based on field tests in the UK, Castleton et al. (2010) find that older buildings with poor insulation benefit more from green roofs than newer structures built to higher insulation standards. Wilkinson and Reed (2009) suggest that the overshadowing caused by buildings in city centers may mean lower potential for green roof retrofits compared to installations in suburban areas and smaller towns with lower rise buildings. Benvenuti and Bacci (2010) highlight the availability of water as the main limiting factor in the realization of green roofs.

A recent meta-analysis suggests that green roofs and parks may have limited effects on cooling. Findings on green roofs were mixed; some studies, but not all, showed lower temperatures above green sections. An urban park was found to be about 1°C cooler than a non-green site and larger parks had a greater cooling effect. Yet studies were mainly observational, lacking rigorous experimental designs. It remains unclear whether there is a simple linear relationship between a park's size and its cooling impact (Bowler et al., 2010) .

Cool roofs or white reflective roofs use bright surfaces to reflect shortwave solar radiation, which lowers the surface temperature of buildings compared to conventional (black) roofs with bituminous membrane (Saber et al., 2012). There is also some work on roads and pavements with increased reflectivity (Foster et al., 2011b). Some studies have quantified the cooling benefits from white roofs in various urban settings—in Hyderabad (Xu et al., 2012), in Sicily (Romeo and Zinzi, 2011), and in the North American climate (Saber et al., 2012). Comparisons between green and white roofs have also been undertaken. Ismail et al. (2011) investigated their cooling potential on a single-story building in Malaysia, and Zinzi and Agnoli (2012) explored the difference in a Mediterranean climate. Results suggest that local conditions play a dominant role in determining the best treatment. Hamdan et al. (2012), for instance, found a layer of clay on top of the roof as the most efficient for passive cooling purposes in Jordan, compared to two different types of reflective roofs.

8.3.3.8. Adapting Public Services and Other Public Responses

As city risk and vulnerability assessments become more common and detailed, they provide a basis for assessing how policies and services can adapt. Section 8.2 noted health impacts that can arise or be exacerbated by climate change that will increase demands on health care systems—including those linked to air pollution, extreme weather, food or water contamination, and climate-sensitive disease vectors. For air quality, additional research is still needed to understand the complex links between weather and pollutants in the context of climate change (Harlan and Ruddell, 2011). Important synergies can be achieved through combining mitigation and adaptation strategies to improve air quality, reduce private transport, and promote healthier lifestyles (Harlan and Ruddell, 2011; see also Bloomberg and Aggarwala, 2008).

In responding to disasters, health care and emergency services (including ambulance, police, and fire fighting) will have increased workloads while also ensuring that their systems can adapt. Their effectiveness can be enhanced by good working relationships with other key government sectors and with civil protection services including the army and the Red Cross/Red Crescent national societies. For cities without a robust early warning system or an emergency response network, adapting to climate change may require significant improvements in staffing, resources, and preparedness plans, for example, the data and personnel to deal with vulnerable residents during heat waves. Particular attention may be required to provide emergency services for informal settlements lacking adequate roads or infrastructure and, when needed, evacuation plans for all those that have to move. There is little evidence of consideration to changes in services in response to climate change in the city case studies listed in Box 8-1.

Enhanced emergency medical services may help cope with extreme events while health officials can also improve surveillance, forecast the health risks and benefits of adaptation strategies, and support public education campaigns. Public health systems may need to increase attention to disease vector control (e.g., screening windows, eliminating breeding grounds for the mosquitoes that are vectors for malaria and dengue) and bolster food hygiene measures linking to increased flooding and temperatures. The costs of adapting health care systems may be considerable—for instance, modifying buildings and equipment, training staff, and setting up comprehensive surveillance and monitoring systems that can capture the health risks of climate change, as well as other risks.

Schools and day-care centers may need risk and vulnerability assessments. School buildings can be designed and built to serve as safe shelters during floods or storms to which those at risk can move temporarily—although it is also important after a disaster to quickly reestablish functioning schools both for the benefit of children and their parents (Bartlett, 2008).

8.4. Putting Urban Adaptation in Place: Governance, Planning, and Management

This section discusses what we have learned about introducing adaptation strategies into the decision processes of urban governments, households, communities, and the private sector. Many aspects of adaptation can be implemented only through what urban governments do, encourage, allow, support, and control. This necessarily involves overlapping responsibilities and authority across other levels of government as well (Dietz et al., 2003; Ostrom, 2009; Blanco et al., 2011; Corfee-Morlot et al., 2011; McCarney et al., 2011; Kehew et al., 2013). Approaches include new urban policies and incentives for action, as well as ensuring that existing policies reduce risk and vulnerability (Urwin and Jordan, 2008; Bicknell et al., 2009; Brugmann, 2012). Transformation should be considered where fundamental change to economic, regulatory, or environmental systems is seen as the most appropriate mechanism for reducing risk and where maintaining existing systems offers little scope for adaptation (Pelling and Manuel-Navarrete, 2011), for instance resettlement or abandonment of previously developed land.

City governments that have developed adaptation policies recognize the value of an iterative process responsive to new information, analyses, or frameworks (National Research Council, 2010). In a range of cities, it has proved useful to have a unit responsible for this within city government, drawing together relevant data, informing key politicians and civil servants, encouraging engagement by different sectors and departments, and consulting with key stakeholders (Roberts, 2010; Brown et al., 2012).

The capacity of local authorities to work effectively, alone or with other levels, is constrained by limited funding and technical expertise, institutional mechanisms, and lack of information and leadership (Gupta et al., 2007; Carmin et al., 2013). Established development priorities and planning practices in functions like land-use, construction, or infrastructure provision may not be aligned with the goals or practice of adaptation (Ostrom, 2009; Pelling, 2011a; Garschagen, 2013). Many national governments face comparable constraints and still do not recognize the importance of local governments in adaptation (OECD, 2010). Local adaptive capacity can benefit from disaster risk reduction (Schipper and Pelling, 2006; UNISDR, 2008). New national legislation and institutions on disaster risk reduction have helped in some cases to strengthen and support local government capacity (Section 8.3.2.2), but as with other forms of adaptation, they require budgetary support and an increase in local professional capacities to be effective locally (Johnson, 2011).

8.4.1. Urban Governance and Enabling Frameworks, Conditions, and Tools for Learning

Enabling conditions and frameworks to support urban adaptation are grounded in institutional structures, values and local competence, interest, awareness, and analytical capacity (Moser and Luers, 2008; Birkmann et al., 2010). Preconditions for sound adaptation decision making relate to principles of good urban government (what government does) and governance (how they work with other institutions and actors including the private sector and civil society) (OECD, 2010; Bulkeley et al., 2011; Garschagen and Kraas, 2011). This includes science-policy deliberative practice and vulnerability assessment (National Research Council, 2007, 2008, 2009; Renn, 2008; Adger et al., 2009; Kehew, 2009; Moser, 2009; Corfee-Morlot et al., 2011). Civil society has important roles, for instance through community risk assessment, and the incorporation of local knowledge, preferences, and norms (Tompkins et al., 2008; van Aalst et al., 2008; Shaw et al., 2009; Fazey et al., 2010; Krishnamurthy et al., 2011). Human behavior, values, and social norms have a role and can evolve through dialog and understanding (Dietz et al., 2003; Moser, 2006; Ostrom, 2009), and engagement with stakeholders over time is key to effective adaptation (Bulkeley et al., 2011; Kehew et al., 2013). This has to allow consideration of dominant development trajectories and alternatives that can be approached by transformative adaptation. The capacity to act within urban settings varies with the organizational context for development (Section 8.1, Table 8-2), including the level of decentralization (Blanco et al., 2011; Corfee-Morlot et al., 2011; McCarney et al., 2011).

8.4.1.1. Multi-Level Governance and the Unique Role of Urban Governments

A framework for urban governance emerges from the challenges that climate change brings to multilevel risk governance. Figure 8-4 summarizes key actors and their relationships. Here, knowledge, policy, and action are produced through the interaction, across scales, of three kinds of actors (based on Corfee-Morlot et al., 2011):

- Knowledge producers (academic science, community, business, and non-governmental organization (NGO) produced research)
- Knowledge actors or users (most important here is local government often in collaboration with partners)
- Knowledge filters who can mediate between knowledge production and action (the media, lobby groups, and boundary organizations that help in translation) (Carvalho and Burgess, 2005; Leiserowitz, 2006; Ashley et al., 2012).

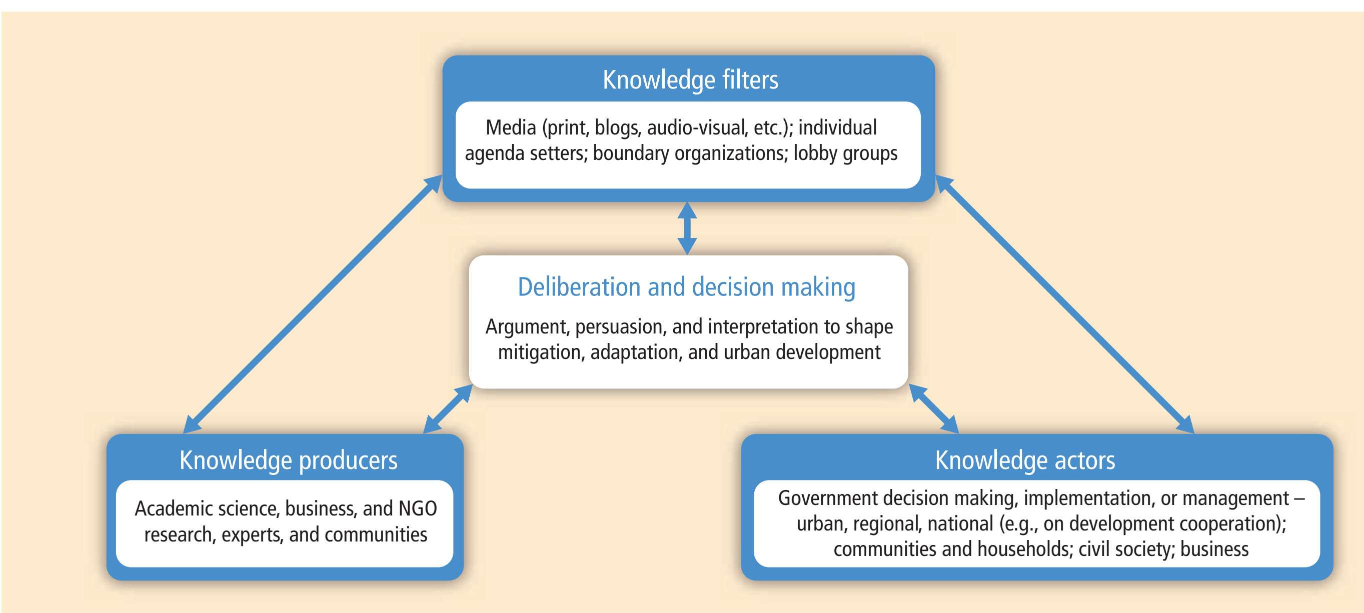


Figure 8-4 | The co-production of knowledge and policy for adaptation, mitigation, and development in urban systems (adapted from Corfee-Morlot et al., 2011).

Urban governments, provided with authority for relevant policy decisions, are central to this process (Blanco et al., 2011; Corfee-Morlot et al., 2011; McCarney, 2012; Kehew et al., 2013). Good practice also hinges in part upon the credibility, legitimacy, and salience of science policy processes; a strong local evidence base of historical and projected data on climate change; and ongoing, open processes to support dialog between government, civil society, and expert advisors (Cash and Moser, 2000; Cash et al., 2006; National Research Council, 2007; Preston et al., 2011; Kehew et al., 2013; see also Chapter 2). Timely and salient communication is important where a key role is played by the media, lobby groups, and boundary organizations that "translate" scientific or expert information for local communities and sometimes also help to shape the questions of scientific inquiry (Jasanoff, 1998; Gieryn, 1999; Moser, 2006; Moser and Dilling, 2007; Moser and Luers, 2008). Good governance facilitates the mediation of policy and decision processes across these different actors, spheres of influence, sources of information, and resources, to co-produce knowledge and support learning and action over time.

While urban governments have authority for many relevant adaptation decisions, they can be enabled, bounded, or constrained by national, subnational, or supranational laws, policies, and funding and land use and infrastructure planning decisions (OECD, 2010; Brown, 2011; Carter, 2011; Martins and da Costa Ferreira, 2011; Arup and C40, 2012; Kehew et al., 2013). This includes establishing formal mandates for urban adaptation action, without which adaptation becomes optional or discretionary, dependent on local-level interest and resources, and particularly vulnerable to leadership change. Where mandates for adaptation exist, they have been important in driving local level action (Kazmierczak and Carter, 2010). New mandates (formal or informal) may also require institutional changes (Roberts, 2008; Lowe et al., 2009; Kazmierczak and Carter, 2010).

The level of complexity is raised in large metropolitan areas, especially when they are growing rapidly. Action has to be coordinated and harmonized across multiple urban jurisdictions; often dozens of them (e.g., Mexico City, São Paulo, London, and Buenos Aires) and occasionally hundreds (e.g., Abidjan and Tokyo) (McCarney et al., 2011; McCarney, 2012), for instance to implement flood protection of contiguous land areas (Hallegatte et al., 2011b). Although there is some evidence of innovative responses at subnational levels to plan for extreme weather events and climate change, limited capacity and experience at local government level suggests the need for support from higher levels of government (Norman and Nakanishi, 2011; EEA, 2012; Gurran et al., 2012).

Policies and incentives need to be aligned to work coherently across multiple levels of government to define and deliver effective urban adaptation. This often involves institutions at different levels with different scopes of authority (Young, 2002; Bulkeley and Kern, 2006; Cash et al., 2006; Mukheibir and Ziervogel, 2007; Urwin and Jordan, 2008; Kern and Gotelind, 2009; Corfee-Morlot et al., 2011; EEA, 2012). Water authorities, for instance, may operate at water-basin level, representing both national and local interests while operating independently of urban authorities. Failing to ensure consistent alignment and integration in risk management can lock in outcomes that raise the vulnerability of urban populations, infrastructure, and natural systems even where pro-active adaptation policies exist (Urwin and Jordan, 2008; OECD, 2009; Benzie et al., 2011). Local government capacity is important, as well as the institutions that facilitate coordination across multiple, nested, poly-centric authorities with potential to mainstream adaptation measures and tailor national goals and policies to local circumstances and preferences. Horizontal coordination and networking across actors and institutions in different municipalities and metropolitan areas can accelerate learning and action (Aall et al., 2007; Lowe et al., 2009; Schroeder and Bulkeley, 2009).

Consultation and awareness-raising can help avoid the kind of public backlash that occurred when the French government sought to ban urban development and require strategic retreat in areas of risk to coastal flooding after the 2010 storm Xynthia (Laurent, 2010; Przyluski and Hallegatte, 2012). There can also be vested interests and trade-offs where near-term development conflicts with longer-term adaptation and resilience goals. Public engagement, openness, and transparency can help ensure democratic debate to balance public interests and longer-term goals against the short-term benefits of unconstrained development. Urban governments are uniquely situated to understand local contexts, raise local awareness, respond to citizens' and civil society pressures, and work to build an inclusive policy space (Grindle and Thomas, 1991; Brunner, 1996; Cash and Moser, 2000; Brunner et al., 2005; Healey, 2006). Urban governments can also promote understanding of climate change risk and help to create a common vision for the future (Moser, 2006; Moser and Dilling, 2007; Ostrom, 2009; Corfee-Morlot et al., 2011). The fact that preferences are more homogeneous within smaller units (Ostrom, 2009) provides opportunities for leadership and innovation that may not exist at higher levels of governance. Urban governments, so often responsible for a substantial share of urban infrastructure (Arup and C40, 2012; Hall et al., 2012), are also central to the interface between climate change and development, including provision for essential infrastructure and services (Bulkeley and Kern, 2006; Bulkeley, 2010). Urban planning structures, processes, and plans can integrate and mainstream adaptation plans and risk management into urban and sectoral planning with a clear time frame, mandate, and resources for implementation (Agrawala and Fankhauser, 2008; Bicknell et al., 2009; Brugmann, 2012), even if functional authority is at national or subnational regional levels (Hall et al., 2012). Many urban governments show growing awareness and analytical capacity in adaptation planning but there is less evidence in implementation and influence on key sectors (Roberts, 2010).

Local government decisions can be driven by short-term priorities of economic growth and competitiveness (Moser and Luers, 2008) and addressing climate change can mean taking a longer-term perspective (Leichenko, 2011; Pelling, 2011a; Romero-Lankao and Qin, 2011; Viguié and Hallegatte, 2012). Tension also exists between economic growth and the needs of the large, often growing, numbers of ill-served urban poor (Bicknell et al., 2009) whose resilience to climate change will depend on infrastructure and services. The challenges in low- and middle-income countries are exacerbated by relative inattention from international donors to urban policy and development concerns, as they have historically worked through national government planning processes, which may not capture the needs of urban populations (Mitlin and Satterthwaite, 2013). Donors may also prefer visible physical infrastructure projects over local institution and capacity-building investments. Most national governments in high-income countries also have yet to fully embrace local adaptation initiatives (McCarney et al., 2011).

8.4.1.2. Mainstreaming Adaptation into Municipal Planning

Mainstreaming adaptation into urban planning and land use management and legal and regulatory frameworks is key to successful adaptation (Lowe et al., 2009; Kehew et al., 2013). It can help planners rethink traditional approaches to land use and infrastructure design based on past trends, and move toward more forward looking risk-based design for a range of future climate conditions (Kithiia, 2010; Solecki et al., 2011; Kennedy and Corfee-Morlot, 2013), as well as reducing administrative cost by building resilience through existing policy channels (Urwin and Jordan, 2008; Benzie et al., 2011; Blanco et al., 2011). Mainstreaming through local government policies and planning ensures that investments and actions by businesses and households contribute to adaptation (Kazmierczak and Carter, 2010; Sussman et al., 2010; Brown, 2011; Mees and Driessen, 2011). But this must avoid overloading already complex and inadequate planning systems with unrealistic new requirements (Roberts, 2008; Kithiia, 2010); particularly in many low- and middle-income countries, these systems are already stressed by lack of information, institutional constraints, and resource limitations.

Mainstreaming may best be initiated by encouraging pilot projects and supporting experimentation by key sectors within local government. Assigning responsibility to specific departments can make the adaptation (and mitigation) message easier to understand by local governments and other stakeholders and the associated responsibilities and actions clearer and simpler to identify and assign (Roberts, 2010; UN-HABITAT, 2011a; Roberts and O'Donoghue, 2013). Pilot projects and sectoral approaches ground adaptation in practical reality (Roberts, 2010; Tyler et al., 2010; UN-HABITAT, 2011a; Brown et al., 2012). As actors in each sector in local government come to understand their roles and responsibilities, the basis for integration and cross-sectoral coordination is formed.

The literature suggests that opportunities to mainstream climate change into urban planning and development are still largely missed (Sánchez-Rodríguez, 2009). The planning agenda can already be full (Measham et al., 2011). Challenges in information, institutional fragmentation, and resources (Sánchez-Rodríguez, 2009; Wilson et al., 2011) make it difficult to introduce the additional layer of climate change planning (Roberts, 2008; Kithiia, 2010), which may also be seen merely as "add-ons" (Kithiia and Dowling, 2010, p. 474).

Other challenges also limit progress—for instance the lack of leadership and of focal points on urban adaptation (see Section 8.4.3.4 for more detail). In times of economic hardship (e.g., the current recession), local authorities with already limited resources may prioritize conventional economic and development goals over "environmental" issues including climate change adaptation (Shaw and Theobald, 2011; Solecki, 2012). A further challenge is getting the timely evaluation of emerging adaptation measures (Hedger et al., 2008; Preston et al., 2011).

Experience with adaptation programs show they are often more cross-sectoral, cross-institutional, and complex. They operate across a range of scales and timelines; are rooted in local contexts; involve many stakeholders; and include high levels of uncertainty (Roberts et al., 2012; Roberts and O'Donoghue, 2013). Standardized guidelines for action are less relevant and urban adaptation practitioners have identified instead the need for "clarity, creativity, and courage" (ICLEI Oceania, 2008, p. 62). In all instances, where progress on adaptation planning is observed, local leadership is a central factor (Carmin et al., 2009, 2013; Measham et al., 2011).

8.4.1.3. Delivering Co-Benefits

Important opportunities also exist to combine adaptation and mitigation goals in urban housing policies (and the energy sources they draw on), infrastructure investments, and land use decisions—especially in high- and middle-income countries (Satterthwaite, 2011). Co-benefits for mitigation and for transformation require a reconsideration of dominant development pathways and of possible alternatives both within and beyond the urban core, influencing, for instance, local environments along with water basin management and coastal defense regimes (Urwin and Jordan, 2008; OECD, 2010). Examples of positive and negative interactions between urban adaptation and mitigation strategies suggest that these strategies will need to be assessed and managed to achieve co-benefits (Viguié and Hallegatte, 2012; Kennedy and Corfee-Morlot, 2013). Viguié and Hallegatte (2012) demonstrate that despite trade-offs, careful planning can yield adaptation-mitigation co-benefits across greenbelt policies, flood zoning, and transportation policies. Local governments may be able to address both adaptation and mitigation using pre-existing tools and policies such as building standards, transport infrastructure planning, and other urban planning tools (Hallegatte et al., 2011a). It may be possible to avoid or limit trade-offs by developing institutional links between the different policy areas at the level of local planning (Swart and Raes, 2007; Viguié and Hallegatte, 2012; Kennedy and Corfee-Morlot, 2013).

Adaptation can produce development co-benefits in urban areas including safer, healthier, and more comfortable urban homes and environments and reduced vulnerability for low-income groups to disruptions in their incomes and livelihoods (Kousky and Schneider, 2003; Bicknell et al., 2009; Burch, 2010; Clapp et al., 2010; Roberts, 2010; Anguelovski and Carmin, 2011;Hallegatte et al., 2011a). Local development co-benefits may be particularly important to highlight in low- and middle-income countries, where lack of policy buy-in accompanies limited local capacity (UN-HABITAT, 2011a) and where current climate change challenges appear marginal compared with development deficits (Roberts, 2008; Kithiia and Dowling, 2010; Kiunsi, 2013). Urban authorities in India can see adaptation as a priority if it also addresses development and environmental health concerns (Sharma and Tomar, 2010).

Development and climate change adaptation are often seen as separate challenges in a subnational planning context. A review in OECD countries showed only Japan and South Korea championing climate action as integral to subnational development planning, although Finland and Sweden have innovative subnational climate policies and action programs funded by central government (OECD, 2010). For most OECD countries, urban development and adaptation are tackled separately. Yet policy research finds that successful adaptation is rooted within and harmonized with such development priorities as poverty reduction, food security, and disaster risk reduction (Moser and Luers, 2008; Bicknell et al., 2009; Measham et al., 2011).

8.4.1.4. Urban Vulnerability and Risk Assessment Practices: Understanding Science, Development, and Policy Interactions

A critical aspect of urban climate risk governance is the integration of scientific knowledge into decision making, building on exchange among scientists, policymakers, and those at risk (Vescovi et al., 2007; National Research Council, 2009; Government of South Africa, 2010; Rosenzweig and Solecki, 2010). International policy advisory agencies with an interest in urban adaptation can augment this (Sonover et al., 2007; ICLEI, 2010), but will depend on local capacity and engagement to produce, access, and use climate change information and processes (Hallegatte et al., 2011a; Carmin et al., 2013). Local and regional boundary organizations can be influential in making scientific and technical information more salient to decision makers (Bourque et al., 2009; Corfee-Morlot et al., 2011). In many instances, key boundary functions are carried out by nearby academic or research communities and these can also be a source of leadership for urban adaptation (Sánchez-Rodríguez, 2009; Government of South Africa, 2010).

Even where detailed vulnerability or risk assessments exist, their influence may be limited if decision makers do not access and use this information. Urban master plans or strategic plans with a time horizon of 10 or more years can incorporate climate risks and vulnerabilities, but assessments must be available to influence such plans. Moser and Tribbia (2006), exploring how decision makers access and use information, find that resource managers tend to rely more on informal sources (maps or in-house experts, media, and Internet) than on scientific journals. This reinforces the point made earlier in regard to producers of scientific and information and knowledge actors to needing to work closely with decision makers in the production and communication of scientific information (Cash et al., 2003, 2006; Moser, 2006; Corfee-Morlot et al., 2011).

8.4.1.5. Assessment Tools: Risk Screening, Vulnerability Mapping, and Urban Integrated Assessment

Assessments of risk and vulnerability to the direct and indirect impacts of climate change are often the first step in getting government attention, especially when put in the context of development policy objectives (Hallegatte et al., 2011a; Mehrotra et al., 2011a; see also Section 8.2). Including risk management information in infrastructure design at the planning or design phase can mean lower retrofit costs later on (Baker, 2012; World Bank, 2012). A variety of planning and assessment tools can be helpful, including impact assessment, environmental audits, vulnerability mapping, disaster risk assessment and management tools, local agenda 21 plans, and urban integrated assessment as part of public investment planning and as used by community organizations (Haughton, 1999; UN-HABITAT, 2007; Baker, 2012). Governments can ensure that up-to-date climate information is available to the private sector to support adaptation (Agrawala et al., 2011; see also Section 8.4.2.3). Some of these tools provide entry points and a means for participatory engagement, but often give little consideration to adaptation (Gurran et al., 2012). More reliable, specific, and downscaled projections of climate change and tools for risk screening and management can help engage relevant public sector actors and the interest of businesses and consumers (AGF, 2010a; UNEP, 2011).

Local climate change risk assessments, vulnerability, and risk mapping can identify vulnerable populations and locations at risk and provide a tool for urban adaptation decisions (Ranger et al., 2009; Hallegatte et al., 2011a; Livengood and Kunte, 2012; Kienberger et al., 2013). The LOCATE methodology (Local Options for Communities to Adapt and Technologies to Enhance Capacity), which integrates hazard and vulnerability mapping to inform choices about which populations, infrastructure, and areas to prioritize for action (Annecke, 2010) is being tested in eight African countries; in each, an NGO is working with communities on across-project design and implementation, monitoring, evaluation, and learning.

Tools that organize and rank information on vulnerability in different locations often aim to identify relative and absolute differences in risk and resilience capacity (Milman and Short, 2008; Hahn et al., 2009; Posey, 2009; Manuel-Navarrete et al., 2011). They vary from quick screenings to fuller risk analyses and evaluations of adaptation options (Hammill and Tanner, 2011). Preston et al. (2011), noting the wide variety of functions and methods in 45 vulnerability mapping studies, suggest that effectiveness is guided by identifying clear goals, robust technical methods, and engagement of the appropriate user communities. Halsnæs and Trærup (2009) recommend the use of a limited set of indicators; engagement with representatives of local development policy objectives; and a stepwise approach to address climate change impacts, development linkages, and economic, social, and environmental dimensions. Methods for application across scale (Kienberger et al., 2013), considering the urban environment as a system, allow for better understanding of interconnections between root causes, risk production, cascading impacts, and vulnerabilities (Kirshen et al., 2008; UNISDR, 2011; da Silva et al., 2012).

Downscaling of climate scenarios, systems models, and urban integrated assessment modelling at local scales integrate information in a forward-looking framework to support urban policy assessment (e.g., van Vuuren et al., 2007; Dawson et al., 2009; Hall et al., 2010; Hallegatte et al., 2011a; Walsh et al., 2011; Viguié and Hallegatte, 2012). Integrated assessment modelling considers the driving forces of urban vulnerability and climate change impacts alongside possible policy responses and their outcomes. By integrating knowledge, this provides a tool for policy makers to examine and better understand synergies and trade-offs across policy strategies (Dawson et al., 2009; Viguié and Hallegatte, 2012). These modeling frameworks take time to build and to be incorporated into decision-making processes. Although early results are promising, they also highlight the difficulty of producing tools that can be easily used by local governments (e.g., see also Hall et al., 2012; Walsh et al., 2011, 2013).

Despite growing attention, useful assessment of climate change at urban spatial scales is generally lacking (Hunt and Watkiss, 2011). A small number of cities, largely in high-income countries, have quantified

Frequently Asked Questions

FAQ 8.4 | Shouldn't urban adaptation plans wait until there is more certainty about local climate change impacts?

More reliable, locally specific, and downscaled projections of climate change impacts and tools for risk screening and management are needed. But local risk and vulnerability assessments that include attention to those risks that climate change will or may increase provide a basis for incorporating adaptation into development now, including supporting policy revisions and more effective emergency plans. In addition, much infrastructure and most buildings have a lifespan of many decades so investments made now need to consider what changes in risks could take place during their lifetime. The incorporation of climate change adaptation into each urban center's development planning, infrastructure investments and land use management is well served by an iterative process within each locality of learning about changing risks and uncertainties that informs an assessment of policy options and decisions.

local climate change risks; even fewer have quantified possible costs under different scenarios. Some exceptions exist: Durban has developed a benefit-cost model for adaptation options (Cartwright et al., 2013), and there have been urban climate risk assessments in low- or middle-income developing countries as part of targeted development cooperation programs, supported by external partners (World Bank, 2011, 2013). Sea level rise and coastal flood risk, health, and water resources are among the most studied sectors; energy, transport, and built infrastructure get far less attention (Hunt and Watkiss, 2011; World Bank, 2011, 2013; Roy et al., 2012). Science and climate change information is increasingly available, but socioeconomic drivers of vulnerability and impacts, and opportunities and barriers to adaptation are less well studied and understood (Measham et al., 2011; Romero-Lankao and Qin, 2011).

8.4.2. Engaging Citizens, Civil Society, the Private Sector, and Other Actors and Partners

8.4.2.1. Engaging Stakeholders in Urban Planning and Building Decision Processes for Learning

A common vision of a future resilient, safe, and healthy city can be the first step to achieving it (Moser, 2006; Moser and Dilling, 2007; Corfee-Morlot et al., 2011; UN-HABITAT, 2011a). Participatory processes figure prominently in cities that have been leaders in urban adaptation (Rosenzweig and Solecki, 2010; Brown et al., 2012; Carmin et al., 2012b). The conceptual literature agrees that participatory decision making is essential where uncertainty and complexity characterize scientific understanding of policy problems (Funtowicz and Ravetz, 1993; Liberatore and Funtowicz, 2003). Many have argued that the institutional features of the risk management decision-making process—participatory inclusiveness, equity, awareness raising, deliberation, argument, and persuasion—will determine the legitimacy and effectiveness of action (Dietz et al., 2003; Lim et al., 2004; Mukheibir and Ziervogel, 2007; Corfee-Morlot et al., 2011). Yet the review of 45 vulnerability mapping exercises found that only 40% included stakeholder participation, raising questions about the legitimacy and salience of contemporary approaches (Preston et al., 2011). It also highlights the challenge local governments face to garner resources, including technical expertise and institutional capacity, to organize and use participatory processes to strengthen rather than delay adaptation decision making (Carmin et al., 2013).

In many urban settings, civil society and the private sector already have significant and positive roles in support of adaptation planning and decisions. Some studies show that despite limited information, adaptation at urban scale is moving ahead, particularly through initial planning and awareness raising (Lowe et al., 2009; Anguelovski and Carmin, 2011; Hunt and Watkiss, 2011). Experience in a handful of cities—for example, Cape Town, Durban, London, New York—shows that a wide number and variety of engaged stakeholders at early stages in a risk assessment creates political support and momentum for follow-up research and adaptation planning (Rosenzweig and Solecki, 2010; Anguelovski and Carmin, 2011; Hunt and Watkiss, 2011). In informal settlements with little or no formal infrastructure and services, stakeholder engagement is a means for participatory community risk assessment, where local adaptive capacity is built in part through local knowledge (Livengood and Kunte, 2012; Kiunsi, 2013). Over time, institutional mechanisms can be built that support innovation, collaboration, and learning within and across sectors to advance urban adaptation action, but it takes time and resources (Mukheibir and Ziervogel, 2007; Burch, 2010; Roberts, 2010; Anguelovski and Carmin, 2011).

8.4.2.2. Supporting Household and Community-Based Adaptation

In well-governed cities, community groups and local governments are mutually supportive, providing information, capacity, and resources in maintaining local environmental health and public safety, which in turn can support adaptation. Where local government has not yet formulated an adaptation strategy, community groups can raise political visibility for climate risks and provide front-line coping (Wilson, 2006; Granberg and Elander, 2007), and also begin to address gender disparities in urban risks (Björnberg and Hansson, 2013).

The full range of infrastructure and services needed for resilience is generally affordable only in middle- and upper-income residential developments in low- and lower-middle income countries. In most cities and neighborhoods, where infrastructure coverage is incomplete and household incomes limited, community organizations—or community-based adaptation—offer a rich resource of adaptive capacity to cope and to prepare for future risk. A range of studies document the depth of knowledge and capacities held by local populations around reducing exposure and vulnerability (Anguelovski and Carmin, 2011; Dodman and Mitlin, 2011; Livengood and Kunte, 2012). For a high proportion of the households that live in informal urban settlements, household and community-based adaptation is their only means of responding to risk. They are well used to coping with environmental hazards (Wamsler, 2007; Adelekan, 2010; Jabeen et al., 2010; Livengood and Kunte, 2012; Kiunsi, 2013). Some seek to modify hazards or reduce exposure—for example, through ventilation and roof coverings to reduce high temperatures; barriers to prevent floodwater entering homes; keeping food stores on top of high furniture; and moving temporarily to safer locations (Douglas et al., 2008). A study in Korail, one of Dhaka's largest informal settlements, showed the range of household responses to flood risk (see Figure 8-5). These include barriers across door fronts, increasing the height of furniture, building floors or shelves above the flood line, and using portable cookers (Jabeen et al., 2010). Provision for ventilation, creepers, or other material on roofs and false ceilings helped to keep down temperatures. These are important near-term adaptations, and there are similar responses in many informal settlements (e.g., Adelekan, 2010; Kiunsi, 2013), but they do not generate capacity to adapt to future risk.

There are multiple constraints on action for low-income households. Even where there are early warnings, a lack of trust in the security of their property and the right to return, along with fears for personal safety in shelters, are deterrents against evacuation (Jabeen et al., 2010; Hardoy et al., 2011). Tenants and those with the least secure tenure are often among the most vulnerable and exposed to hazards but also are usually unwilling to invest in improving the housing they live in and less willing to invest in community initiatives. Community-based responses are often reactive, addressing current more than future risks, though they may embody alternative development values and support local transformation. Shifting the burden of adaptation to the community level alone is unlikely to bring success. There are limits to what community action can do in urban areas. For instance, communities may build and maintain local water sources, toilets, and washing facilities or construct or improve drainage (see for instance the programs in cities in Pakistan described in Hasan, 2006) but they can neither provide the network infrastructure on which these depend (e.g., the water, sewer, and drainage mains and water treatment) nor can they improve city-region governance (Bicknell et al., 2009). Work on cities in the Caribbean and Latin America indicates the need for supportive links to community networks and/or local government for community-level adaptation to be effective (Pelling, 2011b; Mitlin, 2012).

There is some recognition that strengthening the asset base of low-income households helps increase their resilience to stresses and shocks, including those related to climate change (Moser and Satterthwaite, 2009). It has become more common for local governments to work with community-based organizations in upgrading their homes and settlements in disaster risk reduction (UNISDR, 2009, 2011; IFRC, 2010; Pelling, 2011b), and community-based adaptation is building on these experiences and capacities (Archer and Boonyabancha, 2011; Carcellar et al., 2011). Communities can have close relationships with formal state and market institutions, shaping subsequent adaptive capacity for members. Most housing and infrastructure upgrading programs mean that those living in low-income settlements become incorporated into "the formal" city and this often means an increased expectation on the state to reduce vulnerability, including long-term and strategic adaptation investments through access to schools, health care, infrastructure, and safety nets (Ferguson and Navarrete, 2003; Imparato and Ruster, 2003; Boonyabancha, 2005; UN Millennium Project, 2005; Fernandes, 2007; Almansi, 2009).

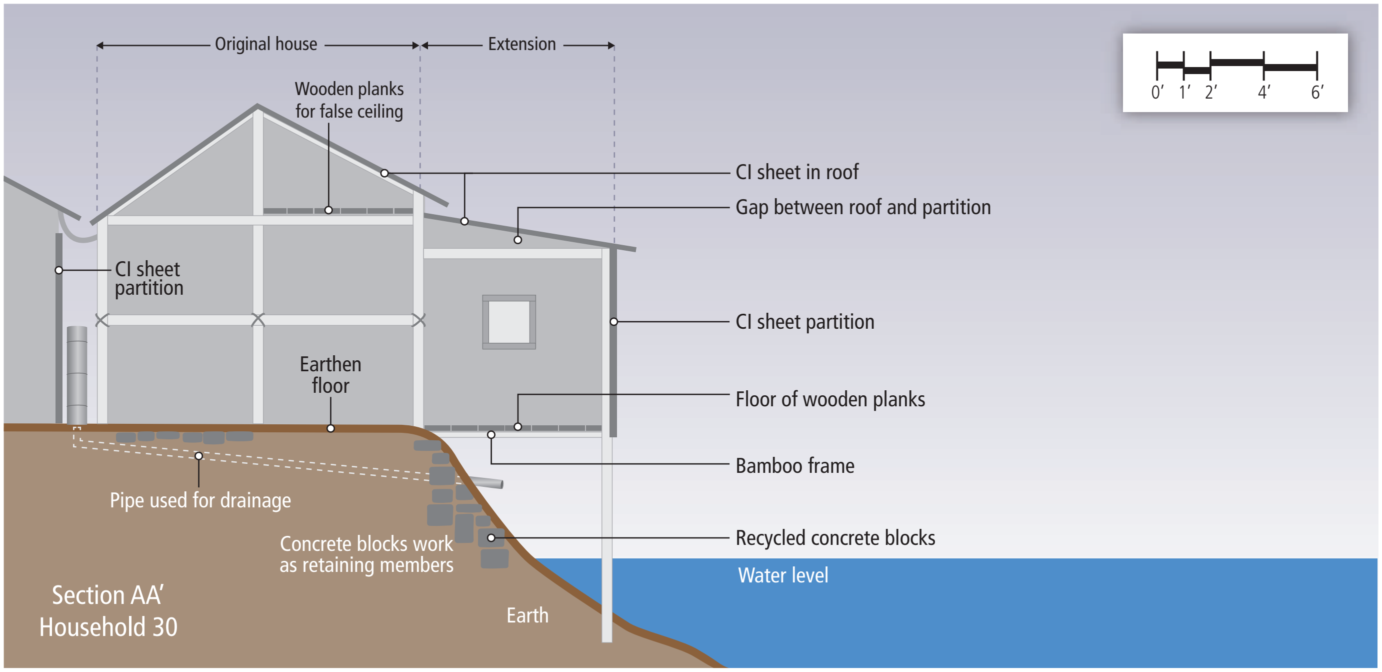


Figure 8-5 | Household adaptation—a cross-section of a shelter in an informal settlement in Dhaka (Korail) showing measures to cope with flooding and high temperatures (Jabeen et al., 2010). CI = corrugated iron.

There can still be obstacles. Where climate change or disaster risk is seen as distant or low probability, the immediate pressures of poverty tend to dominate local agendas (Banks et al., 2011). In many informal settlements, the issue of land tenure is also difficult to resolve and impedes upgrading programs (Boonyabancha, 2005, 2009; Almansi, 2009) and thus local-level adaptation action.

In a growing number of cities, residents' organizations supported by grassroots leaders and local NGOs are mapping and enumerating their informal settlements with eventual support and recognition from city governments (Patel and Baptist, 2012). This provides the data and maps needed to plan the installation or upgrading of infrastructure and services. Some of these enumerations also collect data on risks and vulnerabilities to extreme weather and other hazards (UN-HABITAT, 2007; Carcellar et al., 2011; Pelling, 2011b; Livengood and Kunte, 2012). For example, community surveys in the Philippines identified at-risk communities under bridges, in landslide-prone areas, on coastal shorelines and river banks, near open dumpsites, and in flood-prone locations (Carcellar et al., 2011). This mapping raises awareness among inhabitants of the risks they face, as well as getting their engagement in planning risk reduction and making early warning systems and emergency evacuation effective (Pelling, 2011b). Table 8-4 illustrates the contemporary limits of community-based action across key sites of coping and adaptation—highlighting where strategic partnerships, especially with a supportive municipal government, have key advantages.

IFRC (2010) identifies three broad requirements for successful urban community-based disaster risk reduction that can be extended to assess coping and adaptive capacity: the motivation and partnership of stakeholders; community ownership, with flexibility in project design; and sufficient time, funding, and management capacity. The effectiveness of community-based action also depends on how representative and inclusive the community leaders and organizations are (Appadurai, 2001; Wamsler, 2007; Banks, 2008; Houtzager and Acharya, 2011; Mitlin, 2012); their capacity to generate pressure for larger changes within government; and the relations between community organizations and government (Boonyabancha and Mitlin, 2012). Community-based adaptation can support transformation where it engages with key development agendas to reduce poverty and vulnerability (Sabates-Wheeler et al., 2008), and can address local inequalities and adverse power relations at district, city, national, and transnational levels (Mohan and Stokke, 2000). But urban governance regimes are often resistant to change and civil society organizations can be marginalized or co-opted, reducing the scope for transformative adaptation (Pelling and Manuel-Navarrete, 2011).

8.4.2.3. Private Sector Engagement and the Insurance Sector

Cities are attractive to private enterprises because so much business activity, private investment, and demand are concentrated there. Private enterprises generally favor cities with functioning city infrastructure and a wide range of services. As noted earlier, much investment for sound adaptation will need to come from households and firms of all sizes (Agrawala and Fankhauser, 2008; Bowen and Rydge, 2011). Brugmann (2012) argues that effective adaptation depends on catalyzing market-based investments. Beyond acting to protect their own interests, businesses are stakeholders in urban decision making, positioned to exploit new opportunities that arise from climate change (Chapter 14; see also Khattri et al., 2010). Private service providers and professional associations—including architects, engineers, and urban planners—can influence the pace and quality of adaptation efforts where an understanding of climate change is part of professional training and knowledge (McBain et al., 2010). Even when considering more political

Table 8-4 | The possibilities and limitations of focused activity for community groups on climate change coping and adaptation.

Capacity/focus of action	Coping: drawing on existing resources to reduce vulnerability and hazardousness and contain impacts from current and expected risk.	Adaptation: using existing resources and especially information to reorganize future asset profiles and entitlements to better position the household in light of anticipated future risk, and to prepare for surprises.
Physical: buildings and critical community-level infrastructure	Often possible to improve these although tenants will have little motivation to do so.	Limits in how much risk reduction is possible within settlement (i.e., without trunk infrastructure to connect to).
Physical: land and environment	Local hazard reduction through drain cleaning, slope stabilization, etc. is a common focus of community-based action (although there are fewer incentives where the majority of residents are short-term tenants or threatened with eviction).	External input required to design local hazard reduction works in ways that will consider the impacts of climate change 20 years or more in the future.
Social: health, education	Many examples of community-based action to improve local health and education access and outcomes, often with strong NGO and/or local government support.	Health care and education are amenable to supporting adaptation by providing long-term investments in capacity building. They are rarely framed in climate change adaptation terms.
Economic: local livelihoods	Livelihoods routinely assessed as part of household assessments of coping capacity in urban areas. More rarely is there a local livelihood focus for community-based coping.	Livelihoods and wider economic entitlements are key to individual adaptive profiles, but are seldom considered as part of urban community-based adaptation programs.
Institutional: community organization	Local community strengthening is a common goal of interventions aimed at building coping capacity. Risk mapping, early warning, risk awareness, community health promotion, and shelter training are common foci increasingly applied to urban communities. Local savings groups may have important roles.	Local community strengthening is a core element of planning for adaptation but there are few assessments of the medium-/long-term sustainability of outcomes. Where these have been undertaken, close ties to wider civil society networks or supportive local government were evident and these helped community organizations and actions to persist.
Institutional: external influence	It is unusual for coping programs to include an element of external advocacy aimed at changing policy or practices in local government.	Despite being core to determining future adaptation, there are very few examples of urban community based adaptation projects that include a targeted focus or parallel activity aimed at shifting priorities and practices in local government and beyond to support community capacity building.

Key: green = many cases of activity; amber = few cases of activity; red = very few cases of activity.

issues around the support of adaptation efforts (AGF, 2010b,c), most studies conclude that the need for adaptation investments will far exceed available funds from public budgets (Chapter 15; see also Agrawala and Fankhauser, 2008; World Bank, 2010d; Hedger, 2011).

For markets to favor urban adaptation, the private sector will need to see financial justification for involvement, for example, to ensure business continuity. A survey of companies on the most serious risks they faced (Aon, 2013) ranked weather/natural disasters 16th and climate change 38th although some higher ranked risks such as commodity prices (8th) or distribution/supply chain failure (14th) may be associated with climate change. Risk rankings differed by region (in Asia Pacific weather/natural disasters were 8th) and by sector (for agribusiness, weather/natural disasters were 2nd). Failure of climate change adaptation (as 'governments and business fail to enforce or enact effective measures to protect populations and transition businesses impacted by climate change') was listed by World Economic Forum (2013, p. 46) as one of the most likely environmental risks over the next 10 years and with having a high impact if the risk was to occur. Private sector actors may not be well positioned to consider the big adaptation questions, including changes in land use, development, and infrastructure planning (Redclift et al., 2011). For example, in Cancun, Mexico, close relationships between government and the corporate sector and the push for lucrative development have perpetuated an urban development model that generates climate change risk by increasing the hazard exposure of capital intensive, large-scale coastal development (Manuel-Navarrete et al., 2011). Without transformative change in urban development planning, private sector investments in adaptation will remain limited, such as designing buildings to withstand hurricanes but not tackling where development occurs. In the Cancun case, most investment comes from the state, for example, in beach replenishment and policies for rapid disaster recovery (Manuel-Navarrete et al., 2011).

The Private Sector Initiative of the UNFCCC Nairobi Work Programme offers support for businesses to integrate climate change science into their business planning, including in urban infrastructure and technology developments (http://unfccc.int/adaptation/nairobi_work_programme/private_sector_initiative/items/6547.php). This shows that both public and private (including civil society) actors can have a role in providing regional data and projections of socioeconomic trends, climate change, urban water supply and management practices, land use and building trends, and hazard mapping (UNEP, 2011). A review shows anecdotal evidence of large businesses investing in vulnerability assessments, yet few beginning to invest in adaptation (Agrawala et al., 2011). While some private sector actors take action against climate change risks, many postpone upfront investments for longer-term benefits against uncertain risks. Eakin et al. (2010) and Chu and Schroeder (2010) suggest that the private sector becomes more prominent when local governments and civil society action is limited, but this raises the issue of what incentives are required, especially in regard to low-income countries and communities.

Particularly in wealthier countries and communities, insurance markets can share and spread financial risk from climate change, for example, to help limit damages and manage risks in urban flood-prone areas (Rosenzweig and Solecki, 2010; see also Chapters 10 and 14). Risk-differentiated property insurance premiums can incentivize individuals and businesses to invest in adaption and retrofitting property or to avoid building in high-risk areas (Mills, 2007, 2012; Fankhauser et al., 2008). Relevant insurance instruments include health and life insurance for individuals; property and possession insurance for home and commercial property owners; and micro-insurance or micro-finance mechanisms to support those in low-income urban communities that are not covered by commercial insurance (see Box 8-3). Catastrophe bonds may be developed to cover some urban climate risks, but experience to date suggests they are quite narrowly written for specific events in specific locations, not providing the broad protection necessary to limit catastrophic risk in a changing climate and urban context (Keogh et al., 2011; Brugmann, 2012). Multicat Mexico 2009 is a catastrophe bond used to reinsure the Natural Disaster Fund covering the Mexican territory against hurricanes and earthquakes. This provides resources to mitigate losses up to US$50 million for hurricanes (Aragón-Durand, 2012). The insurance industry can also help shape urban adaptation initiatives, collaborating with building owners, developers, and governments to inform and encourage action.

Private investment or standard insurance markets will not protect low-income urban dwellers (Ranger et al., 2009; Hallegatte et al., 2010). For example, around half of Mumbai's population lives in informal settlements mostly without protective infrastructure and at increasing risk of flooding under most climate change scenarios (McFarlane, 2008; Hallegatte et al., 2010; Ranger et al., 2011). This population (and most of those living in informal settlements in other cities) will not be served by insurance because of the low ability to pay, high risks, and the high transaction costs for companies of administering many small policies. Low-income groups rely instead on local solidarity and government assistance when disaster hits (Hallegatte et al., 2010). In addition, where risk levels exceed certain thresholds, insurers will abandon coverage or set premiums unaffordable to those at risk. Insurance reduces the net risk and loss potential in urban areas, but can also increase inequality in security within neighborhoods or across cities unless coupled with government action to help manage risk in low-income communities (da Silva, 2010).

In many informal settlements, informal savings groups give members (mostly women) quick access to emergency loans (Mitlin, 2008). Where access to formal banking is limited, but social capital is high, those living in informal settlements have also pooled their savings for collective investments that reduce risk in their settlements or allow them to negotiate land and support for new homes (Manda, 2007; d'Cruz and Mudimu, 2013; Satterthwaite and Mitlin, 2014).

For the private sector to fulfill its potential to facilitate urban adaptation, public policy may need to establish enabling conditions in markets (see also Section 8.3), for example, targeting payment for provision of ecosystem services to deliver urban adaptation benefits that otherwise fall outside the market system. Such services include storm buffering and flood protection by paying for mangrove protection in coastal zones or urban green space along river-ways (Fankhauser et al., 2008; Roberts et al., 2012). In building construction, well-documented examples of market failure exist. Private investment in weather proofing new construction and retrofitting existing stock may fail to occur without regulatory intervention. This is an area where municipal governments often have authority to act. Public policy and funding is also needed to

Box 8-3 | Micro-finance for Urban Adaptation

Micro-finance schemes may contribute to pro-poor, urban adaptation through a variety of different instruments including micro-credit, micro-insurance, and micro-savings to help households and small entrepreneurs without access to formal insurance or commercial credit markets. These have been applied mostly in rural areas, usually benefitting those with some property (and thus not the poorest of rural populations). As Hammill et al. (2008, p. 117) state: "*The value MFS holds for climate change adaptation is in its outreach to vulnerable populations through a combination of direct and indirect financial support, and through the long-term nature of its services that help families build assets and coping mechanisms over time, especially through savings and increasingly through micro-insurance—products and sharing of knowledge and information to influence behaviours.*" Although typically more costly than commercial loans, micro-finance can support entrepreneurial undertakings by those unable to get bank loans, help diversify local economies, and empower women in particular, which can in turn contribute to adaptive capacity in a local context (Agrawala and Carraro, 2010; Moser et al., 2010). Micro-finance also provides a means for donors to deliver support to low-income groups without creating an ongoing dependence on aid. But there is a need to target it well to avoid encouraging growth in areas prone to climate risk (Hammill et al., 2008; Agrawala and Carraro, 2010). A limitation of micro-finance for adaptation is that it typically provides credit to individuals, so it is not easily used to finance collective investments—for instance, improving drainage—and it can be a route to indebtedness during disaster recovery. There has been some experience of pooling savings, for example, in low-income communities to set up City Development Funds in Asia, from which they can draw loans for disaster rehabilitation among other things (Archer, 2012). Von Ritter and Black-Layne (2013) explore the possible role for microfinance and crowd funding to support local climate change action e.g. finance small decentralized energy solutions or "climate-proof" homes; they also suggest the new Green Climate Fund could support such activity through its private sector window.

protect the poorest and most vulnerable households, and to ensure or enable action by the private sector. This may include filling gaps in insurance markets (Mills, 2007; Fankhauser et al., 2008; IPCC, 2012; UN-HABITAT, 2011c); helping provide information about risks particularly where this is highly uncertain; and encouraging pro-active engagement by the private sector, as in the UK where vulnerability assessment is required for infrastructure investments (Agrawala et al., 2011). There are examples of urban governments leading by example, requiring the integration of adaptation considerations into public operations and infrastructure investments through procurement requirements, which in turn affects private sector providers. Thus, even where markets exist and are well-functioning, all levels of government may need to engage the private sector in adaptation. Public-private initiatives also have a role providing educational and skill development resources to ensure that the professional networks of private service providers are trained in the latest decision tools, assessment methods, and practices (McBain et al., 2010; da Silva, 2012). Where markets do not exist or do not function well, there will be an even larger role for policy and public investments to support urban adaptation.

8.4.2.4. Philanthropic Engagement and Other Civil Society Partnerships

Philanthropic and other civil society support for urban adaptation is gaining momentum at all levels. The most diverse and numerous are local actions undertaken by community-based organizations, as described above. Philanthropic organizations demonstrate the enabling role that can be played by international civil society to support urban adaptation, particularly in cities and communities in low- and lower-middle-income countries. The coming together of grassroots civil society organizations to form international collaborations and networks can also strengthen the framing role of civil society while retaining local accountability and focus to support adaptation. Some examples include:

- Rockefeller Foundation's support for the Asian Cities Climate Change Resilience Network (ACCCRN) (Moench et al., 2011; Brown et al., 2012)
- The Asian Coalition for Community Action Program managed by the Asian Coalition for Housing Rights
- The Asian Disaster Reduction and Response Network (ADRRN)
- Philippines Homeless People's Federation, working with local governments to identify and help those most at risk to natural disasters (Carcellar et al., 2011)
- Shack/Slum Dwellers International (SDI), a network of community-based organizations and federations of the urban poor in 33 countries in Africa, Asia, and Latin America and their local support NGOs.

Many disaster events are small and local but, taken together, have a widespread and cumulative impact on the development prospects of low-income households and communities, underscoring the need for enhanced civil society engagement and coordination (UNISDR, 2009). Civil society organizations are well placed to address the local conditions and some of the structural root causes of vulnerability, necessary for successful urban adaptation. For example, the scale and range of recent disaster events in Asian cities suggest a growing need for new support mechanisms to facilitate action among local stakeholders—one that should include local government as well as local civil society organizations (Shaw and Izumi, 2011). Where urban civil society is well coordinated and has legitimacy, it can offer alternative models for urban governance and adapting to climate change to assist local governments (Mitlin, 2012). Elsewhere ad hoc coalitions of civil society actors, or even uncoordinated activity in some cities, provide a de facto delivery mechanism for accessing basic infrastructure and rights as part of development and disaster response (Pelling, 2003), although the lack of coordination limits the scale and scope of adaptive capacity. Many civil society initiatives have developed models of infrastructure delivery that are not centered on urban adaptation but have relevance for it, in part through activities designed to reduce disaster risk and increase management capacity (see Hasan, 2006).

8.4.2.5. University Partnerships and Research Initiatives

Since AR4, interest in urban aspects of adaptation has grown in the research community and its funders, as is evident in the number of conferences on this topic, both within social and behavioral sciences and in engineering and city planning sciences. More professional societies are considering their roles and responsibilities. Some cities are tapping into relevant networks; for instance, the Urban Climate Change Research Network (UCCRN) brings together researchers and city planners to exchange knowledge and build a coalition of awareness and policy (Rosenzweig et al., 2010). Other examples include London's use of scenarios generated by UK Climate Impact Programme by University of Oxford's Environmental Change Institute (Carmin et al., 2013); the Urbanization and Global Environmental Change Programme (UGEC) of the International Human Dimensions Programme on Global Environmental Change; the Earth System Science Partnership (ESSP), a pioneer in promoting social science and knowledge exchange; the Land-Ocean Interactions in the Coastal Zone program; Integrated Research on Disaster Risk (IRDR) co-sponsored by the International Council for Science (ICSU), the International Social Science Council (ISSC), and the United Nations International Strategy for Disaster Reduction (UNISDR); and research on urban adaptation in Africa supported by the International Development Research Centre (IDRC).

Individual academic institutes have also begun to support urban adaptation efforts. The Urban Observatory in Manila has become a regional hub for climate change science and urban adaptation; the Universiti Kebangsaan in Malaysia hosts a Malaysian Network for Research on Climate, Environment and Development (MyCLIMATE) focused on awareness and capacity in industry and civil society (Shaw and Izumi, 2011); the Climate and Disaster Resilience Initiative (Kyoto University, CITYNET, and UNISDR) works with city managers and practitioners (Shaw and IEDM Team, 2009); and Latin American networks such as FLACSO (Facultad Latinoamericana de Ciencias Sociales) provide leadership across the region in disaster risk reduction, management, and climate change adaptation. Individual centers have also become more engaged in urban adaptation, for instance, UNAM (Universidad Nacional Autónoma de México) in Mexico and the International Centre for Climate Change and Development (ICCCAD) in Dhaka (Mehrotra et al., 2009; Anguelovski and Carmin, 2011). There remains a challenge to reform university curricula to include urban adaptation and mitigation.

8.4.2.6. City Networks and Urban Adaptation Learning Partnerships

Opportunities for accelerating learning and action may stem from horizontal coordination and networking across actors, professions, and institutions in different municipalities and metropolitan areas. The growing interest in urban adaptation is also seen in the growth of transnational networks and coalitions working across organizational boundaries to influence outcomes, both nationally and internationally (Bulkeley and Betsill, 2005; Bulkeley and Moser, 2007; Rosenzweig et al., 2010) and providing an institutional foundation to concerted effort and collaboration at the city level (Aall et al., 2007; Romero-Lankao, 2007; Kern and Gotelind, 2009). ICLEI's Cities for Climate Protection has been extensively analyzed in the literature (Betsill and Bulkeley, 2004; Lindseth, 2004; Betsill and Bulkeley, 2006; Aall et al., 2007) with a broad conclusion that they are influencing decision making and offer an effective means of sharing experience and learning. Other examples include the Climate Alliance, the C-40 Large Cities Climate Leadership Group, and the Urban Leaders Adaptation Initiative in the USA (OECD, 2010). The United Cities and Local Governments (UCLG) network, representing local governments within the United Nations, also has a growing interest in adaptation. The Asian Cities Climate Change Resilience Network, mentioned above, also encourages inter-city learning for officials and local researchers (Brown et al., 2012). The Making Cities Resilient network, supported by the UN International Strategy for Disaster Risk Reduction (UNISDR), promotes a 10-point priority agenda for city governments, building on good risk reduction practices (UNISDR, 2008; see also Johnson and Blackburn, 2013). Another example of the influence of city networks is the signing of the Durban Adaptation Charter in December 2011 by 107 mayors representing more than 950 local governments at COP17 (Roberts and O'Donoghue, 2013), signaling their intention to begin addressing climate change adaptation in a more concerted and structured way (Rosenzweig et al., 2010). The initial focus of some city networks was on mitigation but attention and leadership on adaptation is growing (as in the U.S. Urban Leaders Adaptation Initiative; Foster et al., 2011a).

8.4.3. Resources for Urban Adaptation and Their Management

Resources for urban adaptation action can come from public and private sectors, domestic and international. Table 8-5 summarizes the main funding sources and financial instruments. In high-income countries, local governments are responsible for an estimated 70% of public spending in urban areas and roughly 50% of public spending on environment infrastructure, often in partnership with other levels of government (OECD, 2010). The scale and source of funds contributing to adaptation varies widely by location and depends in part on the extent to which local authorities can tax residents, property owners, and businesses. A survey of 468 cities conducted by Carmin et al. (2012a) found that most (60%) are not receiving any financial support for their adaptation actions. Of the small percentage of cities receiving funding, the most common source of support is from national governments (24%). A smaller number of cities (9%) reported funding from subnational governments while others (8%) reported support from private foundations and non-profit organizations; only 2 to 4% of the cities reported receiving financial support from international (bilateral and multilateral) financial institutions such as multilateral development banks and this varied widely by region (Carmin et al., 2012a). Some of the environmental innovation in Latin America over the last 20 years is associated with decentralization that has strengthened fiscal bases for cities, along with more elected mayors and more accountable city governments (Campbell, 2003; Cabannes, 2004); Latin American cities have also reported multilateral development banks as the most prevalent source of funding for adaptation representing about 21% of funding to date (Carmin et al., 2012a). In Africa and Asia, a high proportion of urban governments still have very limited investment capacities, as most of their revenues go to salaries and other recurrent expenditures (UCLG, 2011). UCLG data points to the large difference in annual expenditure per person by local governments, ranging from more than US$6000 in some high-income nations to less than US$20 in most low-income nations (UCLG, 2010).

As Table 8-5 indicates, large cities with strong economies and administrative capacity can best attract external funding (including transfers from higher levels of government) and raise internal funding for adaptation. Less prosperous and smaller urban centers and cities with fragmented governance structures or administrations lacking in capability have worse prospects. A key issue is "unfunded mandates"—responsibilities assigned to cities with no increase in funding and capacity (UCLG, 2011)—and this can happen with new responsibilities around climate change (Kehew et al., 2012; Tavares and Santos, 2013). Funding regimes and supportive legal frameworks need to integrate urban climate change risk management and adaptation into development.

8.4.3.1. Domestic Financing: Tapping into National or Subnational Regional Sources of Funding and Support

For adaptation specifically, domestic public funding is one of the most significant and sustainable sources in many countries. Initiatives to green local fiscal policies are spreading, including congestion charges on motor vehicles and value-capture land taxes that make the cost of environmental externalities visible, and/or the benefits of infrastructure and services to property owners (e.g., transport, water, and wastewater services). Such measures can promote private investment in risk management while mobilizing local revenue sources. Local fiscal incentives can lead to maladaptation where urban government budgets and actions are financed by land sales, which in turn promote urban sprawl or development in areas at risk (Drejza et al., 2011; Merk et al., 2012). Greening local fiscal policies will need to identify and address these kinds of concerns.

Grants, loans, and other revenue transfers from national or regional (subnational) governments are also important sources, for instance to compensate local governments for the spillover environmental benefits of their expenditures (OECD, 2010; Hedger, 2011; Hedger and Bird, 2011). An example is municipal funding in Brazil, where the allocation of tax revenues is based on ecosystem management performance (Box 8-3).

Other innovative financial mechanisms for urban adaptation include revolving funds and the energy services company ("ESCO") model (OECD, 2010). Revolving funds can be developed from a variety of revenue streams such as Clean Development Mechanism projects (Puppim de Oliveira, 2009), and savings from energy efficiency investments in

Table 8-5 | Main sources of funding and financial instruments for urban adaptation.

Sources of funding	Types	Instruments	What can be funded (with some examples of funds)	Urban capacity required to access funding
Local: public	Local revenue raising policies: taxes, fees, and charges or use of local bond markets	• Local taxes (e.g., on property, land value capture, sales, businesses, personal income, vehicles…) • User charges (e.g., for water, sewers, public transport, refuse collection) • Other charges or fees (e.g., parking, licenses)	• Urban infrastructure and services • Urban adaptation programs and planning processes • Urban capacity building	Cities with well-functioning administrative and institutional capacity and adequate funding from local revenue generation and intergovernmental transfers
Local: public-private	Public-Private Partnerships (PPP) contracts and concessions	• Concessions and private finance initiatives to build, operate, and/or maintain key infrastructure • Energy performance contracting	Medium to large-scale infrastructure with strong private goods (to allow rents for private sector)	Cities with strong capacity for legal oversight and management
Local or national: private or public	National or local financial markets	• Commercial loans • Private bonds • Municipal bonds	Basic physical infrastructure (need for collateral)	Well-functioning local or national financial markets that city governments can access
National: public	National (or state/ provincial) revenue transfers or incentive mechanisms	• Revenue transfers from central or regional government • Payment for ecosystem services or other incentive measures	• Urban payment for environmental services in Brazil • Sweden's KLIMP climate investment program	Cities with good relations with national governments, strong administrative capacity to design and implement policies and plans
International: private	Market-based investment	• Foreign direct investment, joint ventures	• Industrial infrastructure • Power generation infrastructure	Cities with strong national enabling conditions and policies for investment
International sources	Grants, concessional financing (e.g., Adaptation Fund)	• Grants, concessional loans, and loan guarantees through bilateral and multilateral development assistance • Philanthropic grants	• Urban capacity building • Urban infrastructure adaptation planning	Typically requires strong multi-level governance—cities with good relations with national governments. Cities with low levels of administrative and financial market capacity.

Box 8-4 | Environmental Indicators in Allocating Tax Shares to Local Governments in Brazil

In Brazil, part of the revenues from a value-added state government tax (ICMS) must be redistributed among municipalities. Three-quarters is defined by the federal constitution with the remaining 25% allocated by each state government. The state of Paraná introduced the ecological ICMS (ICMS-E) in 1992 against the background of state-induced land use restrictions (protected areas) for several municipalities, which prevented them from developing land but provided no compensation. For example, 90% of the Piraquara municipality was designated as a protected watershed, supplying the Curitiba metropolitan region with water (May et al., 2002).

States have different systems in place, but there are many commonalities. Revenues are allocated based on the proportion of a municipality's area set aside for protection, and protected areas are weighted according to different categories of conservation management (higher for biological reserves, for instance, than for areas of tourist interest). Paraná and some other states evaluate the protected areas based on physical and biological quality (fauna and flora); quality of water resources; physical representativeness; and quality of planning, implementation, and maintenance.

The ICMS-E, built on existing institutions and administrative procedures, has had very low transaction costs (Ring, 2008). Evaluations show it has been associated with improved environmental management and the creation of new protected areas (May et al., 2002). It has also improved relations with the surrounding inhabitants as they start to see these areas as an opportunity to generate revenue, rather than an obstacle to development.

Adapted from OECD, 2010.

municipal buildings to feed public funds for investments that yield adaptation benefits. Local governments in high- and some middle-income countries may also have direct access to bond markets or loans from national (or regional) development banks or financial institutions (OECD, 2010; Merk et al., 2012). Local access to capital markets can be facilitated through risk-sharing mechanisms or guarantees provided by development banks, for example, the German government's Development Bank KfW provides low-interest loans to local banks which then finance energy-efficient renovations in residential and commercial buildings (OECD, 2010; Pfliegner et al., 2012).

A key challenge is determining how far adaptation funding should be geared to target associated policy realms. The very high costs of extreme weather events in many urban areas, and the fact that climate change usually increases these risks, indicates the need for increased funding and attention from national budgets for risk reduction and early warning and evacuation procedures within urban areas, alongside other adaptation measures (World Bank, 2010a,e; Hallegatte and Corfee-Morlot, 2011). The urban funding gap may be particularly wide for "soft" rather than "hard" infrastructure investments, yet both can be a motor for resilience.

8.4.3.2. Multilateral Humanitarian and Disaster Management Assistance

The international humanitarian community is increasingly active in urban contexts, with relevance for adaptation capacity (IFRC, 2010). Non-climate-related disasters (including earthquakes and tsunamis) provide a learning opportunity, and the sector is beginning to review experience and develop appropriate tools and guidelines for urban contexts (e.g., ALNAP, 2012). In 2009, humanitarian groups formed a reference group on meeting humanitarian challenges in urban areas, setting a 2-year action plan in 2010, and developing a database of urban-specific aid tools, the Urban Humanitarian Response Portal (http://www.urban-response.org/). Policies sensitive to the needs of internally displaced urban populations are a big challenge for the sector, especially where the resident population is chronically poor (Crawford et al., 2010; Zetter and Deikun, 2010); so too are appropriate responses to increased urban food insecurity (Battersby, 2013).

The systematic programming of climate change adaptation into multilateral humanitarian, disaster response, and management funding within development cooperation is in its infancy. Urban dimensions are under-developed although this is changing (UNISDR, 2009, 2011; IFRC, 2010). The World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR) explicitly includes adaptation to climate change. Its Country Programmes for Disaster Risk Management and Climate Change Adaptation 2009–2011, and more recently 2014–2016, seek to deepen engagement in some priority countries (GFDRR, 2009, 2013; World Bank, 2013). The GFDRR, with UNISDR, has also advocated for more integrated policy and advisory services at the technical level (see Mitchell et al., 2010). A 2009–2011 survey of reports from 82 governments on disaster risk reduction and urban and climate change issues found some progress in both areas (Figure 8-6; UNISDR, 2011).

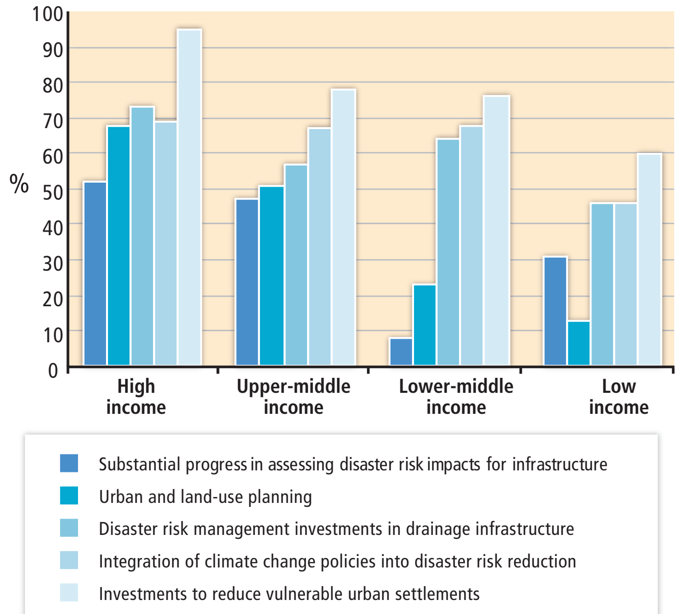


Figure 8-6 | Progress reported by 82 governments in addressing some key aspects of disaster risk reduction by countries' average per capita income (UNISDR, 2011).

Despite progress, many urban governments lack the capacity to address disaster risk reduction and management. Almost 60% of the countries surveyed by the UN (80% of lower-middle-income countries) reported that local governments have legal responsibility for disaster risk management, but only about a third had dedicated budget allocations, mostly in upper-middle- and high-income countries (UNISDR, 2011). Figure 8-6 highlights attention to investments in drainage infrastructure, but much less in urban and land use planning in lower-middle- and low-income countries. Progress in integrating climate change policies into disaster risk reduction was reported by more than two-thirds of governments in high-, upper-middle-, and lower-middle-income countries but under half of low-income countries.

8.4.3.3. International Financing and Donor Assistance for Urban Adaptation

The limited data available show attention to urban areas in the growing levels of international development financing available to support adaptation (e.g., OECD, 2013; World Bank, 2013). Development finance is a key source of support for adaptation in many low- and middle-income countries, but many vulnerable cities and municipalities are poorly positioned to access available funding (ICLEI, 2010; Paulais and Pigey, 2010), for their often very large deficits in risk-reducing infrastructure and services. In some local governments, international programs offer the main source of institutional and financial support for mitigation and adaptation work at the local level, but this can raise the danger of a "donor-driven model" (where the funding agency's agenda does not coincide with local priorities); experience shows that without strong and lasting local ownership, programs are unsustainable once support is withdrawn (Hedger, 2011; OECD, 2012). More international funding for adaptation and mitigation is being committed, largely as Official Development Assistance (ODA), and governments are broadly on track delivering on their international promises (see, e.g., the Cancun Agreements) to scale up international climate finance (Buchner et al., 2012; Clapp et al., 2012). Less in evidence are sound institutional arrangements to make this support available to urban governments. The *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) calls for arrangements that will allow adaptive urban management systems to evolve with changing social and environmental dynamics (IPCC, 2012) but international channels for development finance have yet to adjust to this call to action.

Recent data suggest that a small share of total flows of climate-related ODA targets adaptation (UNEP, 2011; OECD, 2012), and some of this is supporting urban adaptation (e.g., see OECD, 2013; World Bank, 2013). OECD estimates bilateral ODA commitments targeting climate change to be in the range of US$11 to US$20 billion per year on average in 2010–2011 for both adaptation and mitigation; of this, roughly 20 to 40% targets adaptation (OECD, 2013). One in-depth assessment of five major donors, covering concessional and non-concessional finance, estimated adaptation to be 30% of their climate change portfolio, mostly targeted to water and sanitation (about 75%) (UNEP, 2011). The rest were for other relevant sectors (i.e., transport, policy loans, disaster risk reduction), but with energy and health largely overlooked (UNEP, 2011; see also Atteridge et al., 2009). Despite growing attention to climate change, many bilateral agencies have historically had very limited engagement with urban initiatives (Mitlin and Satterthwaite, 2013). Some authors also note the difficulty in distinguishing adaptation from development finance, which limits the accuracy of such estimates (Tirpak et al., 2010; Buchner et al., 2012).

Despite the uncertainties in tracking adaptation ODA, OECD statistics (OECD, 2013) show that there is some attention to urban issues today.[2] Urban adaptation is estimated to represent about 20% of bilateral climate adaptation portfolios, equivalent to US$0.65 to US$1.6 billion per year (on average over 2010–2011). Slightly more than half of this goes to projects in urban centers with between 10,000 and 500,000 inhabitants while the rest goes to large cities with 500,000 or more inhabitants. The major sectors are water (about 38%, considering projects that had adaptation as principal or significant) and sanitation (another 6%) (OECD, 2013). The largest providers of urban adaptation ODA in these years were Japan (an average of US$683 million a year in commitments), Germany (US$333 million); France (US$111 million); and South Korea, European Union Institutions, Spain, and Denmark (between US$48 and US$80 million). The largest recipients were Vietnam (US$232

[2] Data and information as found in the OECD DAC-CRS 2013, www.oecd.org/dac/stats/rioconventions.htm (last accessed: September 7, 2013). These estimates derive from data and project descriptions in the OECD DAC-Creditor Reporting System. It is based on a project-by-project review of qualitative information in the 2013 version of the database describing official development finance from bilateral agencies and the EU institutions. This subset of "urban" adaptation activities describes those projects that identify the geography of beneficiaries as urban and that include a verifiable location (e.g., metropolitan Lima); data were organized by key characteristic of each urban location (i.e., population size and recipient country). Only urban areas with populations of 10,000 or more are included here. Projects are marked with climate adaptation "Rio marker"; this data set includes all projects marked as targeting climate adaptation, either as a principal objective or as those with it as a significant objective.

million); Bangladesh (US$146 million); China (US$100 million); and the Philippines, Peru, Indonesia, and Kenya (US$52 to US$76 million).

Around 70% of urban adaptation aid is dedicated to "hard" infrastructure while about 10% goes to "soft" measures to support capacity building related to urban infrastructure planning and adaptation. So OECD data suggest that urban adaptation is a recent but significant objective in climate aid activities but it is still only a small part of overall ODA portfolios (OECD, 2013).

Conventional channels for development finance appear to have the biggest role in adaptation financing in low- and middle-income countries, though new vertical funds are also emerging. The proliferation of multiple, single purpose funding mechanisms runs contrary to long-standing harmonization principles of sound development cooperation (Hedger, 2011; OECD, 2012). This more complex funding architecture makes it difficult for smaller actors such as local authorities to access sources for timely adaptation investments.

Development assistance can be better targeted if reconciled with bottom-up, locally based planning processes that take climate risks into account, and programs aiming to be mainstreamed into urban development over time (Brugmann, 2012). Research shows the lack of well-defined priorities in partner countries, combined with a donor tendency to "control" funds for short-term results and a large variety of different funding instruments results in fragmented delivery systems and unclear outcomes (Brown and Peskett, 2011). Even where climate strategies exist to guide action—as in Bangladesh, an "early mover" on adaptation planning—the plan is often neither costed nor sequenced, making it an inadequate framework for finance delivery (Hedger, 2011). A key to improving effectiveness of international public finance will be building the capacity for country-led planning processes identifying priority actions for targeting adaptation funds. National Adaptation Plans of Action (NAPAs) have become a principal way of organizing adaptation priorities in Least Developed Countries, but the majority of plans do not explicitly include urban projects and do not reflect local government perspectives (UN-HABITAT, 2011c).

A number of authors conclude that international development finance is failing to tackle urban adaptation financing needs (Parry et al., 2009; Paulais and Pigey, 2010; ICLEI, 2011; UN-HABITAT, 2011c). Some suggest that national governments could set up funds supported by international finance (governmental, philanthropic, or both) and on which urban governments and community-based organizations can draw (Paulais and Pigey, 2010; Satterthwaite and Mitlin, 2014). In some middle-income countries, such as Indonesia, a more effective and sustainable strategy than a focus on external funding may be national policy reforms and incentives to steer investment to priority needs (Brown and Peskett, 2011). There is also a need to mobilize domestic public and private investment to ensure delivery of adaptation at national and urban levels (Hedger, 2011; Hedger and Bird, 2011; OECD, 2012). Accessing all these sources of development finance for urban adaptation will require institutional mechanisms to support multi-level planning and risk governance (Corfee-Morlot et al., 2011; Carmin et al., 2013).

8.4.3.4. Institutional Capacity and Leadership, Staffing, and Skill Development

Leadership is critical for generating interest in urban adaptation and championing awareness and institutional change to bring action (Anguelovski and Carmin, 2011; Carmin et al., 2012a). Creating a climate change and environmental focal point or office in a city can help coordinate climate action across government departments or agencies (Roberts, 2008, 2010; Anguelovski and Carmin, 2011; Hunt and Watkiss, 2011; OECD, 2011; Brown et al., 2012). Yet there may be downsides when this function is housed in the environmental line department—see Durban (Roberts, 2008), Boston (City of Boston, 2011), and Sydney (Measham et al., 2011)—since they are typically among the weakest parts of city government with limited influence (Roberts, 2010).

Although there is growing evidence of urban adaptation leadership (Lowe et al., 2009; Anguelovski and Carmin, 2011; Foster et al., 2011b), there are also important political constraints at the local level. Powerful

Box 8-5 | Adaptation Monitoring: Experience from New York City

The adaptation monitoring approach developed for New York City has four indicator elements: (1) physical climate change variables; (2) risk exposure, vulnerability, and impacts; (3) adaptation measures; and (4) new research in each of these categories. Examples of indicators arising from these categories include the percentage of building permits issued in a given year in current Federal Emergency Management Agency (FEMA) coastal flood zones, and in projected 2080 coastal flood zones; a tally of building permits with measures to reduce precipitation runoff; an index based on insurance data that measures the insurer's perception of the city's infrastructure-coping capacity; an index that measures the rating of city-issued bonds or infrastructure operators for capital projects with climate change risk exposure; the detailed trend of weather-related emergency/disaster losses (whether insured or uninsured, relative to the total asset volume); and the number of days with major telecommunication outages (wireless versus wired), correlated with weather-related power outages. Data criteria were decided through a scientist-stakeholder consensus with designated groups to evaluate prospective indicators and their values. This case study shows the need for interdisciplinary, longitudinal data collection and analysis systems along with an inclusive, transparent process for stakeholder engagement to interpret the data (Jacob et al., 2010).

vested interests may oppose attention to adaptation and promote development on sites at risk. As noted earlier, concerns about employment and competitiveness make it difficult for local governments to focus on the more distant implications of climate change. This is especially so during periods of economic hardship (Shaw and Theobald, 2011; Solecki, 2012). A key step forward is institutionalizing different types of behavior and norms.

Beyond goal setting and planning, the literature also suggests the need for regulatory frameworks to require relevant behavior and investment. Governments can institute small changes, such as job descriptions that require actions and provide incentives to act in new ways (e.g., for line managers and sector policy makers) or by providing training and clear guidance to staff (Moser, 2006; Carmin et al., 2013; Tavares and Santos, 2013). Budgetary transparency and metrics to measure progress on adaptation can also help to institutionalize changes in planning and policy practice (OECD, 2012).

8.4.3.5. Monitoring and Evaluation to Assess Progress

Adaptation leaders and funding institutions need tools for monitoring and evaluating urban adaptation actions to justify investments but these are not well developed yet or widely implemented in urban areas (Kazmierczak and Carter, 2010). This requires indicators that show if adaptation is taking place, at what pace, and in what locations. Relevant evaluation criteria include cost, feasibility, efficacy, co-benefits (direct and indirect), and institutional considerations (Jacob et al., 2010). Assessment methods can capture outcomes of adaptation decisions, or the decision-making processes themselves—ideally both. Monitoring is challenging for adaptation, especially urban, given the lack of standard metrics, the differences in local contexts, and the often localized nature of adaptation (Lamhauge et al., 2012; Spearman and McGray, 2012).

City authorities, NGOs, and researchers have begun to design adaptation monitoring and evaluation frameworks. Box 8-5 presents the experience of New York City. Development of standard tools offers scope for international benchmarking and coordination across scales of assessment, for example, by associating local indicators of resilience with those in the Hyogo Framework for Action (that prioritize disaster risk reduction) and the post-2015 development agenda (IFRC, 2011).

Monitoring and evaluation focusing on the effectiveness of donor aid on climate adaptation is a growing area of research (Chaum et al., 2011; Lamhauge et al., 2012; Spearman and McGray, 2012). Recent work shows the urgent need for consistent and internationally harmonized data collection to support monitoring. This is a concern for both adaptation and wider disaster risk reduction spending, suggesting a systemic challenge to the architecture of international finance (Kellett and Sparks, 2012). Steps are being made through multi-site assessment programs, in some instances including treatment of urban issues. For example, the World Bank recently included an adaptive capacity index as part of an analysis of risk and adaptation options for five cities in Latin America and the Caribbean. The methodology was previously applied in Guyana, where it demonstrated a gap between national and city level adaptive capacity (Pelling and Zaidi, 2013).

Monitoring also needs to consider the delivery and use in cities of international climate finance to ensure that funds are being effectively directed (Chaum et al., 2011; Hedger, 2011). This is especially important for cities at an early stage of planning, implementing, and monitoring of adaptation, as they can learn from one another's experiences. There is some evidence that international agencies overburden partner organizations and countries (including in some cases city authorities) with monitoring requirements; with limited local capacities, this can detract from further program design and implementation.

8.5. Annex: Climate Risks for Dar es Salaam, Durban, London, and New York City

Refer to Table 8-6 for four city profiles of current and indicative future climate risks, covering Dar es Salaam, Durban, London, and New York. Each summarizes the present, near-term (2030–2040), and long-term (2080–2100) climate risks and the potential for risk reduction through adaptation. As noted earlier, data should not be compared between cities but trends in adaptive capacity and impact can be drawn out.

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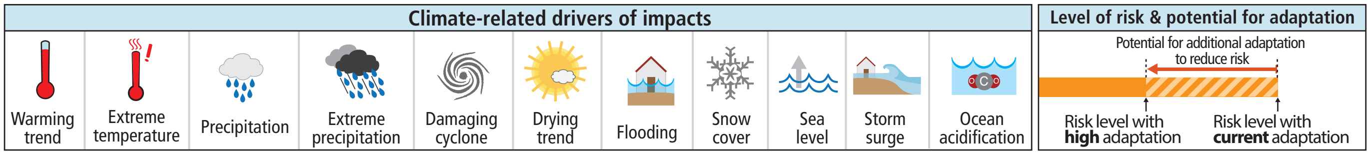
Table 8-6 | Current and indicative future climate risks for Dar es Salaam, Durban, London, and New York City.



Dar es Salaam

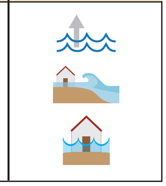
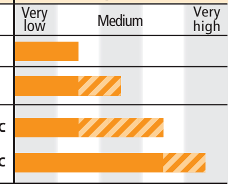
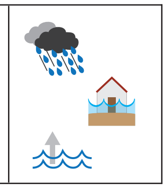
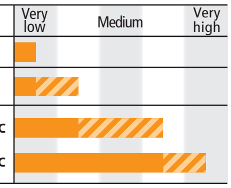
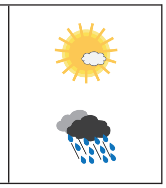
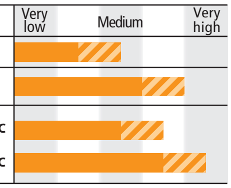
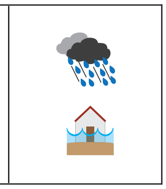
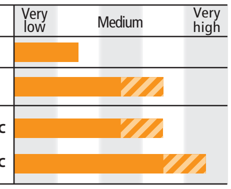
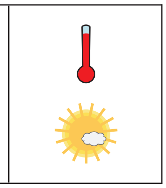
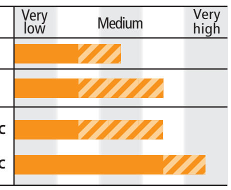
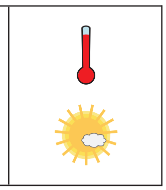
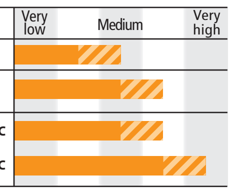
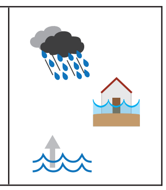
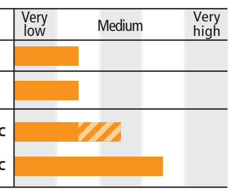
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Coastal zone systems (*medium confidence*) [8.3.3.3, 8.3.3.4]	Construction of coastal protection structures such as sea walls and groynes to minimize coastal erosion and land inundation in Dar es Salaam. Medium prospects due to high costs.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	
Terrestrial ecosystems and ecological infrastructure (*low confidence*) [8.3.3.7, Table 8-2]	Demarcation and protection of green areas, provision of more drainage systems, and protection of urban wetlands and ground water resources. Low prospects due to poor development control including land use management.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	
Water supply systems (*high confidence*) [8.2.4.1, 8.3.3.4, Table 8-2]	Improvement in Dar es Salaam's water resources management and increased coverage and efficiency in water supply systems. Medium prospects as some of these measures are already being implemented.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	
Waste water system (*high confidence*) [8.2.4.1, 8.3.3.4, Table 8.2]	Increase in spatial coverage of sewerage and improvement of on-site excreta disposal systems. Low prospects for extending sewer coverage; higher prospects for expanding onsite disposal systems.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	
Energy systems (*very high confidence*) [8.2.4.2]	Reduced dependence on hydropower as the main source of energy by replacing it with natural gas. Very high prospects as the country has vast resources of natural gas.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	
Food systems and security (*high confidence*) [8.3.3.2]	Urban and peri-urban agriculture and new adaptation policies to take into account impacts of climate change on food costs and supply chain. Enhanced social safety nets can support adaptation measures.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	
Transportation and communication systems (*medium confidence*) [8.2.4.3, 8.3.3.6]	New design standards in context of climate change and enforcement of development controls. Low prospects as climate change issues are yet to be mainstreamed in the sector.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C / 4°C	

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Table 8-6 (continued)

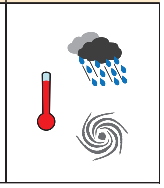
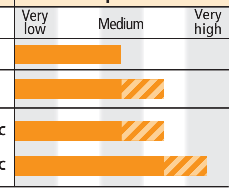
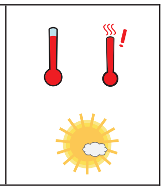
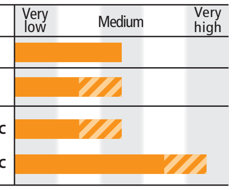
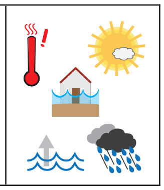
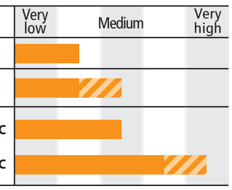
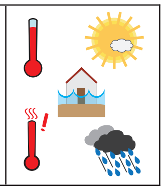
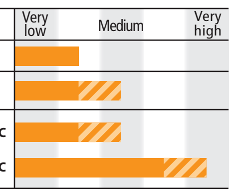
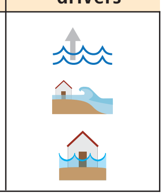
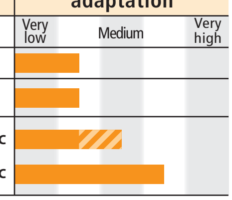
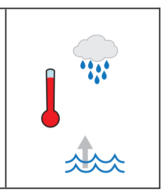
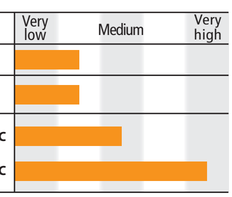
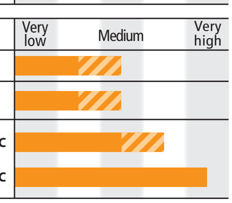
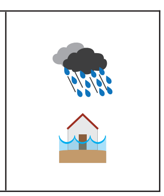
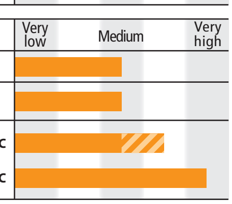
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Dar es Salaam (continued)				
Housing (*high confidence*) [8.2.4.4,8.3.3.3]	Climate change adaptation plans, new building codes, effective development control, and upgrading of informal settlements. High prospects as some of these measures are already being taken into account.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Human health (*medium confidence*) [8.3.3]	Improvement of water supply, solid waste management, housing conditions, land use planning and food security, and provision of health insurance. Medium prospects as these are key development issues that require a lot of financial resources.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Key economic sectors and services (*medium confidence*) [8.3.3.1]	Improvement of storm water infrastructure and transport networks. Use of natural gas as main source for power generation, relocating of key economic activities and infrastructure along coastal buffer areas. A mixture of high and low prospects due to availability of natural gas and high requirements of financial resources.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Poverty and access to basic services (*high confidence*) [8.3.3]	Formalizing informal economic sector, upgrading of informal settlements, improvement of housing conditions and empowering local communities in tackling problems related to climate change. High prospects as this is already being implemented as a development issue.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Durban				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Coastal zone systems (*medium confidence*) [8.3.3.3]	Maintaining and restoring Durban's coastal ecosystems. Use of coastal protection structures such as geofabric sand bags, retaining walls, groynes, and a beach nourishment scheme to minimize coastal erosion and infrastructure damage. Use of a development setback line and in some instances strategic retreat to protect infrastructure. High prospects as systems for coastal protection exist and are being improved, but may be overwhelmed by the increase in severity and frequency of storm surges over time.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Terrestrial ecosystems and ecological infrastructure (*medium confidence*) [8.3.3.4]	Design and implementation of a fine-scale systematic conservation plan to protect a representative and persistent system of local biodiversity and related ecosystem services. Remove non-climate threats e.g., by managing alien invasive species. Medium prospects due to lack of human and financial resources to protect and manage system and poor enforcement of contraventions.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Water supply systems (*high confidence*) [8.3.3.4]	Demand and supply side management required. Reduce non-revenue water losses. Use of ecological infrastructure to improve level of assurance. Medium prospects as measures are already being implemented or considered.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	
Waste water system (*high confidence*) [8.3.3.4]	Increase in spatial coverage of Durban's waterborne sewerage system and use of appropriate alternative services in areas too costly to serve with waterborne systems. Recycling of waste water to potable standards. Medium prospects as measures are already being implemented or investigated.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C / 4°C	

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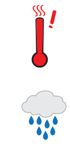
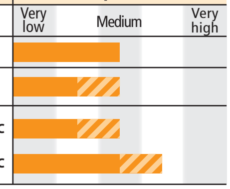
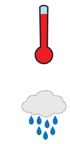
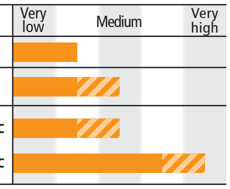
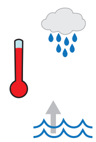
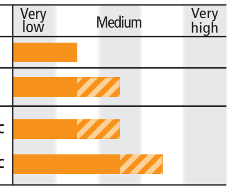
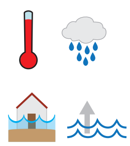
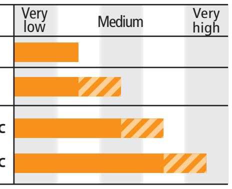
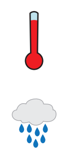
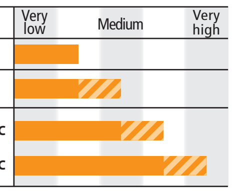
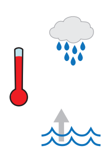
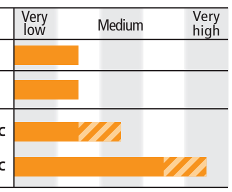
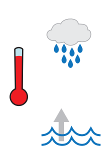
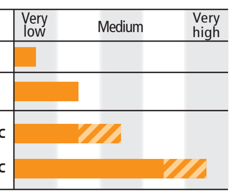
Table 8-6 (continued)

Durban (continued)

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Energy systems (*medium confidence*) [8.3.3.5]	No integration of energy policy with adaptation policy or practice. Need to avoid maladaptation e.g., increased electricity use for cooling in response to rising temperatures. Low prospects as institutional structures not yet in place to drive this integration.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Food systems and security (*high confidence*) [8.3.3.2]	Need to change planting dates and to provide increased crop irrigation. Need to take into account the impacts of climate change on the full food supply chain. Low prospects as climate change not yet considered a serious threat.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Transportation and communications systems (*medium confidence*) [8.3.3.6]	New design standards in context of climate change and enforcement of development control. Medium prospects as climate change issues are beginning to be considered in the transportation sector.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Housing (*high confidence*) [8.3.3.3]	New building codes, effective development control, upgrading of informal settlements, and retrofitting of existing housing stock. Changes in stormwater policy, preparation of master drainage plans, use of attenuation facilities, and calculation of new floodlines. Promotion of higher densities to reduce pressure on ecological infrastructure. Medium prospects as measures are already being implemented or being investigated.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Human health (*high confidence*) [8.3.3]	Improvement of basic services, housing conditions, land use planning, and food security. Extend coverage of primary health care and health insurance. Maintain and extend vector control. Ensure ability to deal with the impacts of large-scale disasters through inter-sectoral coordination. Low to medium prospects due to limited human and financial resources.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Key economic sectors and services (*medium confidence*) [8.3.3.1]	Durban is a logistics, manufacturing, and tourist center. Need to protect and properly locate vulnerable infrastructure in coastal areas, particularly port-related infrastructure. High prospects because of the national economic significance of the port and petro-chemical sectors and local economic significance of tourism.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Poverty and access to basic services (*high confidence*) [Box 8-2, 8.3.3.7]	Formalizing informal economic sector, upgrading informal settlements, provision of interim services to informal settlements, improving housing conditions, and increasing the adaptive capacity of local communities (especially through ecosystem based adaptation). Use of climate change adaptation interventions to create employment opportunities. Medium prospects because of the scale of the problem and related costs.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

London

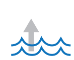
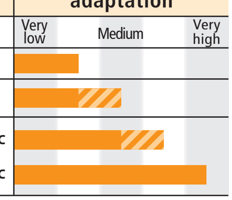
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
River/coastal zone systems (*high confidence*) [8.3.3.4]	London is currently well protected from tidal flooding and has utilized an "adaptation pathways" approach to ensure it identifies and delivers a flexible long-term tidal flood risk management plan to maintain a high standard of protection through the century.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

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Table 8-6 (continued)

London (continued)				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation** (Very low / Medium / Very high)
Terrestrial ecosystems and ecological infrastructure (*medium confidence*) [8.3.3.7]	Adaptation is compromised primarily by habitat fragmentation and can be exacerbated, especially in wetland habitats, by invasive species. The city is taking an approach that promotes the multifunctional benefits of ecologically designed urban green spaces to benefit adaptation with restoring ecological function.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Water supply systems (*high confidence*) [8.3.3.4]	London faces increasing water security issues during droughts created by higher relative per capita consumption, aging infrastructure, a rapidly growing population, and projected diminishing resources. Resilience is being increased through programs to reduce consumption and increase the diversity of supply.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Waste water system (*high confidence*) [8.3.3.4]	Much of London is served by a combined rain and foul water drainage system that regularly overflows into the River Thames. Population growth, urban creep, and projected more intense rainfall will further challenge the system. The city is working with the relevant drainage partners to manage this increasing risk through a combination of gray and green infrastructure.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Energy systems (*medium confidence*) [8.3.3.5	The city's energy security is threatened by a reduction in national generation capacity and the resilience of local distribution systems not matching the increasing demand. The city is responding through increasing energy efficiency and local energy production to improve resilience. Some concern over amplifications effects of energy system failure during heat or cold shocks.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Food systems and security (*low confidence*) [8.3.3.2]	London's food supply is globalized and access is strongly influenced by global food prices relative to income, as well as regional and national agricultural productivity.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Transportation and communication systems (*medium confidence*) [8.3.3.6]	London is served by a complex communications and public transport network, which though vulnerable in parts has sufficient redundancy to be resilient at the strategic level. Detailed risk assessments are informing an investment program in the transport network that will deliver increasing resilience to climate impacts.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Housing (*high confidence*) [8.3.3.3]	London has an extensive historic housing stock that demonstrates poor thermal performance in summer and winter and poor water efficiency. A significant proportion of this housing stock is at risk of flooding. There is improving integration between mitigation and adaptation policy implementation at the regional level, but insufficient funding and levers to implement widespread adaptation.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Human health (*high confidence*) [8.2.2.1, 8.2.3.1]	Health observation systems and care delivered through the National Health Service respond well but need to integrate better with social care provision to be more proactive, especially for vulnerable groups such as the elderly.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

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Table 8-6 (continued)

London (continued)				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Key economic sectors and services (*medium confidence*) [8.3.3.1]	London's economy is dominated by service sector activities, particularly finance and including global businesses that expose it to failure in external markets that may be associated with climate change impacts or management. Business continuity is routinely integrated into business plans. Failure of essential infrastructure, including transport and energy networks, has short-term impacts.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Poverty and access to basic services (*high confidence*) [8.3.3.8]	A significant proportion of the population struggles to pay their energy and water bills. Pockets of deprivation create areas of high vulnerability to climate risks, compounded by low levels of community capacity / social networks.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high

New York City				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Coastal zone systems (*very high confidence*) [8.2]	NYC is highly vulnerable to coastal storm events and sea level rise associated flooding. Integration of infrastructure and policy changes with opportunity to enhance ecosystem service services is possible.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Terrestrial ecosystems and ecological infrastructure (*high confidence*) [8.2.4.5; 8.3.3.4]	Promotion of ecosystem restoration efforts consistent with the current degraded state of most of NYC's ecosystem function. A need exists for continued land use protection of the city's water supply region.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Water supply systems (*medium confidence*) [8.3.3.4, 8.3.3.7]	NYC maintains an extremely extensive and resilient water supply infrastructure. Long-term adaptation could potentially include heightened drought management and interagency coordination with other water supply demand entities in region.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Waste water system (*medium confidence*) [8.2.3.3,8.2.4.1]	NYC maintains an extremely extensive and resilient waste water infrastructure. Gray and green infrastructure adaptation to limit effects of extreme precipitation events and combined sewer overflows will be necessary.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Energy systems (*medium confidence*) [8.2.4, 8.2.4.2]	NYC is served by an extensive energy generation and distribution system, most of which is operated by private companies or semi-public authorities. Peak load demand adaptation, especially for cooling demand will be necessary, as will adaptation for distribution disruptions associated with extreme events including ice storm events and coastal storm surge.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Food systems and security (*medium confidence*) [8.3.3.2]	NYC is connected to a regional, national, and global food distribution system. Adaptation will be necessary to ensure that food processing and distribution systems within the city can be resilient in the face of potential extreme event impacts.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high

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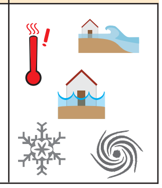
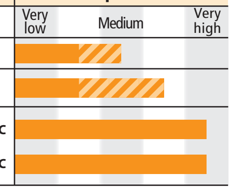
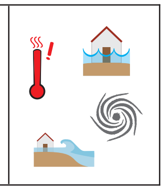
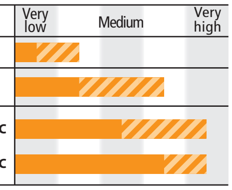
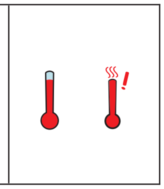
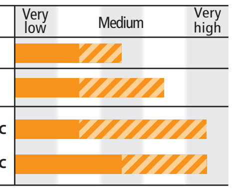
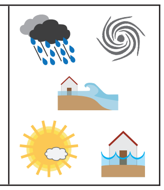
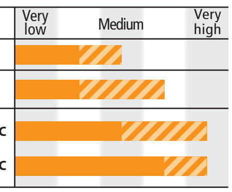
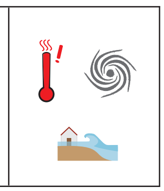
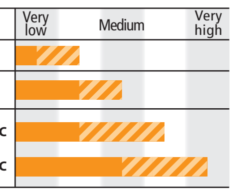
Table 8-6 (continued)

New York City (continued)				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Transportation systems (*high confidence*) [8.2.2.2, 8.3.3.6]	NYC is served by a complex and redundant transportation and communications infrastructure. Numerous vulnerabilities to extreme events are present that result in short-term disruption. Long-term sea level rise and increased flood frequency can result in increased disruption and will require adaptation strategies.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Housing (*high confidence*) [8.1.3, 8.2.4, 8.3.3.3]	NYC includes approximately 1 million buildings and similar structures. These maintain a broad range of vulnerabilities to climate change particularly associated with flooding and extreme heat events. Adaptation strategies could include retrofit construction practices, especially in coastal zone locations or areas affected by urban heat island conditions.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Human health (*high confidence*) [8.2.3.1]	Great diversity of health conditions of the 8.3 plus million residents is associated with a wide range of human health vulnerabilities to climate change. The very young, aged, and otherwise health-compromised face heightened risk and require adaptation strategies, particularly focused on heat stress and disease.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Key economic sectors and services (*medium confidence*) [8.3.3.1]	NYC has a diverse economic base focused on service-related industries with regional, national, and global connections. Adaptation will be necessary to limit vulnerability and enhance resilience in the face of large-scale extreme events such as Hurricane Sandy.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Poverty and access to basic services (*medium confidence*) [8.3.3.8]	NYC has an extensive public service provision capacity. Adaptation will be necessary to ensure that more frequent or more intense extreme events will not limit this capacity.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

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9

Rural Areas

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9

Executive Summary

Rural areas still account for almost half the world's population, and about 70% of the developing world's poor people. {9.1.1} There is a lack of clear definition of what constitutes rural areas, and definitions that do exist depend on definitions of the urban. {9.1.2} Across the world, the importance of peri-urban areas and new forms of rural-urban interactions are increasing (*limited evidence*, *high agreement*). {9.1.3} Rural areas, viewed as a dynamic, spatial category, remain important for assessing the impacts of climate change and the prospects for adaptation. {9.1.1}

Climate change in rural areas will take place in the context of many important economic, social, and land-use trends (*very high confidence*). In different regions, absolute rural populations have peaked or will peak in the next few decades. {9.3.1} The proportion of the rural population depending on agriculture is extremely varied across regions, but declining everywhere. Poverty rates in rural areas are higher than overall poverty rates, but also falling more sharply, and the proportions of population in extreme poverty accounted for by rural people are also falling: in both cases with the exception of sub-Saharan Africa, where these rates are rising. {Figure 9-2} Accelerating globalization, through migration, labor linkages, regional and international trade, and new information and communication technologies, is bringing about economic transformation in rural areas of both developing and developed countries. {9.3.1}

Rural people in developing countries are subject to multiple non-climate stressors, including under-investment in agriculture (though there are signs this is improving), problems with land and natural resource policy, and processes of environmental degradation (*very high confidence*). In developing countries, the levels and distribution of rural poverty are affected in complex and interacting ways by processes of commercialization and diversification, food policies, and policies on land tenure. In developed countries, there are important shifts toward multiple uses of rural areas, especially leisure uses, and new rural policies based on the collaboration of multiple stakeholders, the targeting of multiple sectors, and a change from subsidy-based to investment-based policy. {9.3.1, Table 9-3}

Impacts of climate change on the rural economic base and livelihoods, land use, and regional interconnections are at the latter stages of complex causal chains (*high confidence*). These flow through changing patterns of extreme events and/or effects of climate change on biophysical processes in agriculture and less-managed ecosystems. {9.3.3} This increases both the uncertainty associated with detection and attribution of current impacts {9.3.2}, and with projections of specific future impacts. {9.3.3}

Structural features of farm households and communities affect their vulnerability to climate change in complex ways (*high confidence*). There is *low agreement* on some of the key factors associated with vulnerability or resilience in rural areas {9.3.5.1}, including rainfed as opposed to irrigated agriculture {9.3.5.1.1}, small-scale and family-managed farms, and integration into world markets. {9.3.5.1.2} There is *high agreement* on the importance for resilience of access to land and natural resources, flexible local institutions {9.3.5.1.3}, and knowledge and information {9.3.5.1.6}, and on the association of gender inequalities with vulnerability. {9.3.5.1.5} Specific livelihood niches such as pastoralism, mountain farming systems, and artisanal fisheries are vulnerable and at high risk of adverse impacts (*high confidence*), partly owing to neglect, misunderstanding, or inappropriate policy toward them on the part of governments. {9.3.5.2}

Cases in the literature of observed impacts on rural areas often suffer from methodological problems of attribution, but evidence for observed impacts, both of extreme events and other categories, is increasing (*medium confidence*). Impacts attributable to climate change include some direct impacts of droughts, storms, and other extreme events on infrastructure and health (*low confidence* globally, but *medium confidence* in certain regions), as well as longer-term declining yields of major crops, from which impacts on income and livelihoods can be inferred with *low confidence*. There is *high confidence* in geographically specific impacts, such as glacier melt in the Andes. {9.3.2}

Major impacts of climate change in rural areas will be felt through impacts on water supply, food security {9.3.3.1}, and agricultural incomes {9.3.4.1} (*high confidence*). Shifts in agricultural production, of food and non-food crops, are projected for many areas of the world (*high confidence*). {9.3.3.1} Price rises, which may be induced by climate shocks as well as other factors {9.3.3.3.2}, have a disproportionate impact on the welfare of the poor in rural areas, such as female headed households and those with limited access to modern agricultural inputs, infrastructure, and education. {9.3.3.1} The time scale for impacts varies across regions and sectors, and by the nature of the specific climatic impact.

Climate change will impact international trade volumes in both physical and value terms (*limited evidence*, *medium agreement*). Importing food can help countries adjust to climate change-induced domestic productivity shocks while short-term food deficits in low-income countries may have to be met through food aid. Options exist for adaptations within international agricultural trade (*medium confidence*). Deepening agricultural markets and improving the predictability and the reliability of the world trading system through trade reform, as well as investing in additional supply capacity of small-scale farms in developing countries, could result in reduced market volatility and manage food supply shortages caused by climate change. {9.3.3.3.2}

Migration patterns will be driven by multiple factors of which climate change is only one (*high confidence*). {9.3.3.3.1} Given these multiple drivers of migration (economic, social, political, demographic, and environmental) and the complex interactions that mediate migratory decision making by individuals or households, establishment of a relation between climate change and intra-rural and rural-to-urban migration, observed or projected, remains a major challenge.

Climate policies, such as increasing energy supply from renewable resources, encouraging cultivation of biofuels, or payments under Reducing Emissions from Deforestation and Forest Degradation (REDD), will have significant secondary impacts, both positive (increasing employment opportunities) and negative (landscape changes, increasing conflicts for scarce resources), in some rural areas (*medium confidence*). {9.3.3.4} There is a need to understand how implementation of these policies will impact on rural livelihoods. These secondary impacts, and trade-offs between mitigation and adaptation in rural areas, have implications for governance, including the need to promote participation of rural stakeholders.

Most studies using valuation methodologies conclude that climate change impacts will be substantial, especially for developing countries, owing to their economic dependence on agriculture and natural resources, low adaptive capacities, and geographical locations (*very high confidence*). {9.3.4} Valuation of climate impacts needs to draw on both monetary and non-monetary indicators. The valuation of non-marketed ecosystem services {9.3.4.5} and the limitations of economic valuation models that aggregate across multiple contexts {9.3.4} pose challenges for valuing impacts in rural areas (*high confidence*).

There is a growing body of literature on adaptation practices in both developed and developing country rural areas {9.4.1}, including documentation of practical experience in agriculture, water, forestry and biodiversity, and, to a lesser extent, fisheries {9.4.3} (*very high confidence*). Public policies supporting decision making for adaptation exist in developed and, increasingly, in developing countries, and there are also examples of private adaptations led by individuals, companies, and non-governmental organizations (*high confidence*). {9.4.2} Constraints on adaptation come from lack of access to credit, land, water, technology, markets, knowledge and information, and perceptions of the need to change; and are particularly pronounced in developing countries (*high confidence*). {9.4.4} Gender and institutions affect access to adaptation options and the presence of barriers to adaptation (*very high confidence*). {9.4.4}

9

9.1. Introduction

9.1.1. Rationale for the Chapter

This chapter assesses the impacts of climate change on, and the prospects for adaptation in, rural areas. Rural areas include diverse patterns of settlement, infrastructure, and livelihoods, and relate in complex ways with urban areas. The chapter shows that rural areas experience specific vulnerabilities to climate change, both through their dependence on natural resources and weather-dependent activities and their relative lack of access to information, decision making, investment, and services. Adaptation strategies will need to address these vulnerabilities. Some of the key starting points, which affect the scope and coverage of literature assessed in this chapter, are as follows:

- Rural areas, even after significant demographic shifts, still account for 3.3 billion people, or almost half (47.9%) of the world's total population (UN DESA Population Division, 2013).
- The overwhelming majority of the world's rural population (3.1 billion people, or 91.7% of the world's rural population, or 44.0% of the world's total population) live in less developed or least developed countries (UN DESA Population Division, 2013).
- Rural dwellers also account for about 70% of the developing world's poor people. IFAD (2010) states that around 70% of the extreme poor in developing countries lived in rural areas in 2005. Ravallion et al. (2007), using 2002 data and poverty lines of US$1.08 or US$2.15, in each case with urban poverty lines adjusted upward to recognize additional non-food spending, give a figure of around 75% of people, under either poverty line, being rural.
- Rural areas are a spatial category, associated with certain patterns of human activity, but with those associations being subject to continuous change.
- Rural areas are largely defined in contradistinction to urban areas, but that distinction is increasingly seen as problematic.
- Rural populations have, and will have, a variety of income sources and occupations, within which agriculture and the exploitation of natural resources have privileged, but not necessarily predominant, positions.

The chapter will complement the treatment of issues also dealt with in Chapters 4 and 7, but will primarily look at how biophysical impacts of climate change on agriculture and on less-managed ecosystems translate into impacts on human systems, and in this regard will complement sections of Chapters 12 and 13 and other sectoral and regional chapters. The important impacts of climate change on human health are covered in Chapter 11. In accordance with the proportion of the rural population found in developing countries, literature on these countries is given prominence, but issues of impact, vulnerability, and adaptation in developed countries are also assessed.

9.1.2. Definitions of the Rural

"Rural" refers generally to areas of open country and small settlements, but the definition of "rural areas" in both policy-oriented and scholarly literature are terms often taken for granted or left undefined, in a process of definition that is often fraught with difficulties (IFAD, 2010).

Frequently Asked Questions

FAQ 9.1 | What is distinctive about rural areas in the context of climate change impacts, vulnerability, and adaptation?

Nearly half of the world's population, approximately 3.3 billion people, lives in rural areas, and 90% of those people live in developing countries. Rural areas in developing countries are characterized by a dependence on agriculture and natural resources; high prevalence of poverty, isolation, and marginality; neglect by policymakers; and lower human development. These features are also present to a lesser degree in rural areas of developed countries, where there are also closer interdependencies between rural and urban areas (such as commuting), and where there are also newer forms of land use such as tourism and recreational activities (although these also generally depend on natural resources).

The distinctive characteristics of rural areas make them uniquely vulnerable to the impacts of climate change because:

- Greater dependence on agriculture and natural resources makes them highly sensitive to climate variability, extreme climate events, and climate change.
- Existing vulnerabilities caused by poverty, lower levels of education, isolation, and neglect by policymakers can all aggravate climate change impacts in many ways.

Conversely, rural people in many parts of the world have, over long time scales, adapted to climate variability, or at least learned to cope with it. They have done so through farming practices and use of wild natural resources (often referred to as indigenous knowledge or by similar terms), as well as through diversification of livelihoods and through informal institutions for risk-sharing and risk management. Similar adaptations and coping strategies can, given supportive policies and institutions, form the basis for adaptation to climate change, although the effectiveness of such approaches will depend on the severity and speed of climate change impacts.

Table 9-1 | Indicative examples of definitions of the "rural" and the "urban" in selected countries.

Country	Term	Definition	Reference
Australia	Major urban area	Population of more than 100,000	Australian Bureau of Statistics (2013)
	Other urban area	Population of 1000–99,999	
	Rural area	Includes small towns with a population of 200–999	
China	Major urban area	Population of more than 10,000	Ministry of Construction (1993)
	Medium urban area	Population of 3000–9999	
	Small urban area	Population of fewer than 3000	
	Major village	Population of 1000–3000	
	Medium village	Population of 300–1000	
	Small village	Population of fewer than 300	
India	Urban area	Population of 5000 or more; **or** where at least 75% of the male working population is non-agricultural; **or** having a density of population of at least 400 people km^{-2}. It is implied that all non-urban areas are rural.	Government of India (2012)
Jamaica	Urban place	Population of more than 2000 people; and provision of a certain set of amenities and facilities that are deemed to indicate "modern living". It is implied that all non-urban areas are rural.	Statistical Institute of Jamaica (2012:iv)
United States of America	Rural area	All territory outside of defined urbanized areas and urban clusters, that is, open country and settlements with fewer than 2500 residents; with population densities as high as 386 people km^{-2}.	Womach (2005)

Ultimately, in developing countries as well as developed countries, the rural is defined as the inverse or the residual of the urban (Lerner and Eakin, 2010). Human settlements in fact exist along a continuum from "rural" to "urban," with "large villages," "small towns," and "small urban centers" not clearly fitting into one or the other. The variations in definitions from country to country can best be described through several examples (from both developed and developing countries of different sizes) shown in Table 9-1.

Researchers have increasingly recognized that the simple dichotomy between "rural" and "urban" is extremely problematic (Simon et al., 2006, p. 4). Additional categories such as "peri-urban areas" (Webster 2002; Bowyer-Bower, 2006; Simon et al., 2006; Simon, 2008; Lerner and Eakin, 2010) and "desakota" (McGee, 1991; Desakota Study Team, 2008; Moench and Gyawali, 2008) allow more nuanced analysis of the permeable boundaries of rural and urban areas and the diversified economic systems that exist across the urban-rural spectrum; see Box CC-UR.

While remaining aware of issues of definition, this chapter in general assesses the literature on rural areas using whatever definitions of the rural are used in that literature. Global statistics collated by international organizations and cited here are generally aggregations of national statistics compiled under each national definition.

9.2. Findings of Recent Assessments

The Fourth Assessment Report (AR4) of the IPCC contains no specific chapter on "rural areas." Material on rural areas and rural people is found throughout the AR4, but rural areas are approached from specific viewpoints and through specific disciplines. Table 9-2 summarizes key findings on rural areas from AR4 (particularly Easterling et al. (2007) on agriculture; Wilbanks et al. (2007) on industry, settlement, and society; and Klein et al. (2007) on links between adaptation and mitigation), and relevant findings from the International Assessment of Agricultural Knowledge, Science and Technology for Development (McIntyre et al., 2009). All of these sources stress uncertainty, the importance of non-climate trends, complexity, and context-specificity in any findings on rural areas and climate change.

9.3. Assessing Impacts, Vulnerabilities, and Risks

9.3.1. Current and Future Economic, Social, and Land Use Trends in Rural Areas

Climate change in rural areas will take place against the background of the trends in demography, economics, and governance that are shaping those areas. While there are major points of contact between the important trends in developing and developed countries, and the analytical approaches used to discuss them, it is easier to discuss trends separately for the two groups of countries. In particular there is a close association in developing countries between rural areas and poverty. Table 9-3 summarizes and compares the most important trends across the two groups of countries. Figures 9-1 and 9-2 and Table 9-4 focus on two specific trends in developing countries: demographic trends and trends in poverty indicators.

9.3.2. Observed Impacts

Documentation of observed impacts of climate change on rural areas involves major questions of detection and attribution (see Chapter 18). Whilst having potential, there are complications with using traditional knowledge and farmer perceptions to detect climate trends (Rao et al., 2011; see also Box 18-4). Implied equivalence between local perceptions of climate change, local decadal trends, extreme events, and global change is common, and often used without systematic discussion of the challenges (Paavola, 2008; Ensor and Berger, 2009; Castro et al., 2012). This is not a problem in the context of detailed social-scientific analysis of vulnerability, adaptive capacity, and their determinants, but becomes more problematic to use as evidence for observed impact. Detection and attribution of extreme events to climate change is no less challenging (Seneviratne et al., 2012). Exposure to non-climate trends and shocks further complicates the issue (Nielsen and Reenberg, 2010; see also Section 3.2.7).

The impacts of climate change on patterns of settlement, livelihoods, and incomes in rural areas will be the result of multi-step causal chains of impact. Typically, those chains will be of two sorts. One sort will involve extreme events, such as floods and storms, as they impact on rural infrastructure and cause direct loss of life. The other sort will involve impacts on agriculture or on ecosystems on which rural people depend. These impacts may themselves stem from extreme events, from changing patterns of extremes due to climate change, or from changes in mean conditions. The detection and attribution of extreme events is discussed by the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (Seneviratne et al., 2012). The detection and attribution of impacts on ecosystems and on agriculture are dealt with in Chapters 4 and 7 of this report. Both exercises are complex.

Seneviratne et al. (2012) give a detailed and critical assessment of the detection and attribution of observed patterns of extreme events, which shows greatly varying levels of confidence in the attribution to climate change of global and regional trends, and that "attribution of single extreme events to anthropogenic climate change is challenging" (p. 112). They state that it is *likely* there has been a worldwide increase in extreme high-water events during the late 20th century, with a *likely* anthropogenic influence on it. They have *medium confidence* in detecting trends toward more intense and frequent droughts in some parts of the world (southern Europe and West Africa) since 1950. They note that opposite trends exist elsewhere, and that there is *low confidence* in any trend in drought in, for example, East Africa. WG I AR5 Chapter 2 similarly ascribes *low confidence* in a global observed trend in drought in the later 20th century, with a *likely* increase in frequency and intensity of drought in the Mediterranean and West Africa and a *likely* decrease in central North America. Lyon and DeWitt (2012) see a "recent and abrupt decline in the East African long rains" since 1999. Seneviratne et al. (2012) assign *low confidence* to any observed long-term increases in

Table 9-2 | Relevant findings on rural areas from the IPCC Fourth Assessment Report and the International Assessment of Agricultural Science and Technology for Development.

	Finding	Source
Importance of non-climate trends	The significance of climate change needs to be considered in the multi-causal context of its interactions with other non-climate sources of change and stress (e.g., water scarcity, governance structures, institutional and jurisdictional fragmentation, limited revenue streams for public sector roles, resource constraints, or inflexible land use patterns).	W 7.4.2 I 6.7.5
	Different development paths may increase or decrease vulnerabilities to climate-change impacts.	W 7.7
	Neglect by policymakers and underinvestment in infrastructure and services has negatively affected rural areas.	I 1.3.4
	Policy neglect specifically disfavors rural women.	I 1.3.4
	Assessment of climate change impacts on agriculture has to be undertaken against a background of demographic and economic trends in rural areas.	E 5.3.2
	Global numbers of people at risk from hunger will be affected by climate change, but more by socioeconomic trends as captured in the difference between the SRES scenarios.	E 5.6.5
Specific characteristics of smallholder agriculture	Subsistence and smallholder livelihood systems suffer from a number of non-climate stressors, but are also characterized by having certain resilience factors (efficiencies associated with the use of family labor, livelihood diversity to spread risks).	E 5.3.2
	Traditional knowledge of agriculture and natural resources is an important resilience factor.	I 2.1.2, 3.2.2, 3.2.3 E 5.3.2 CC4
	The combination of stressors and resilience factors gives rise to complex and locally specific impacts, resistant to modeling.	E 5.4.7 W 7.2, 7.4, 7.5
Impacts on agriculture and agricultural trade	In low-latitude regions, temperature increases of 1–2°C are likely to have negative impacts on yields of major cereals. Further warming has increasingly negative impacts in all regions.	E 5.4.2
	Increases in global mean temperatures (GMTs) of 2–3°C might lead to a small rise or decline (10–15%) in food (cereals) prices, while GMT increases in the range of 5.5°C or more might result in an increase in food prices of, on average, 30%.	E 5.6.1
Forestry	Loss of forest resources through climate change may affect 1.2 billion poor and forest-dependent people, including through impacts on non-timber forest products.	E 5.4.5
Valuation	Robust valuation of climate change impact on human settlements is difficult, and social and environmental costs are poorly captured by monetary metrics: non-monetary valuation methods should be explored.	W 7.4.3, 7.5 I 8.2.5
Adaptation	The need and the capacity to adapt vary considerably from region to region, and from farmer to farmer.	I 1.3.3
	Adaptation actions can be effective in achieving their specific goals, but they may have other (positive or negative) effects, including resource competition.	I 6.7.5
	Diversification of agricultural and non-agricultural livelihood strategies is an important adaptation trend, but requires institutional support and access to resources.	E 5.5.1, 5.5.2
	The effectiveness of adaptation efforts is likely to vary significantly between and within regions, depending on geographic location, vulnerability to current climate extremes, level of economic diversification and wealth, and institutional capacity.	I 6.8
	Multi-stakeholder processes are increasingly important with respect to climate change adaptation.	I 7.5.3
Links between adaptation and mitigation	Mitigation and adaptation policies are in many cases, and certainly for agriculture, closely linked.	K 18.4.3, 18.7.1 E 5.4.1, 5.4.2, 5.6.5 W 7.1, 7.7

Sources: W = Wilbanks et al. (2007); E = Easterling et al. (2007); I = McIntyre et al. (2009); K = Klein et al. (2007); CC4 = Cross-Chapter Case Study C4 "Indigenous knowledge for adaptation to climate change" in AR4 (Parry et al., 2007).

tropical cyclone activity, as does WGI AR5 Chapter 2, and to attribution of any changes in cyclone activity to anthropogenic influence. WGI AR5 Chapter 2 states that an observed increase in the frequency and intensity of North Atlantic cyclones is *virtually certain*. It also describes varying regional trends toward heavy precipitation events, *very likely* in central North America. Section 3.2.7 ascribes *medium confidence* to observed increased likelihood of flooding at the scale of some regions.

Handmer et al. (2012) discuss both observed and projected impacts of extreme events on human systems and ecosystems, with numerous examples of diverse, widespread negative impacts (see also Chapter 18). Important categories of extreme events causing negative impacts in rural areas include tropical storms and droughts: Hurricane Stan in October 2005 affected nearly 600,000 people on the Chiapas coast as a consequence of flooding and sudden river overflows (Saldaña-Zorrilla, 2008). Droughts in rural areas produce severe economic stresses, including employment reduction and migration (Gray and Mueller, 2012). Agricultural livelihoods are affected by droughts. Ericksen et al. (2012) review a variety of livestock mortality rates for recent droughts in the Horn of Africa, ranging up to 80% of livestock in southern Kenya in 2009.

Climate change impacts on agriculture and ecosystems run through rising temperature and changes in rainfall variability and seasonality as well as through extreme events. Changes in temperature caused reduction in global yields of maize and wheat by 3.8 and 5.5% respectively from 1980 to 2008 relative to a counterfactual without climate change, which offset in some countries some of the gains from improved agricultural technology (Lobell et al., 2011; see also Section 7.2.1.1). Badjeck et al. (2010) discuss current and future impacts on fisherfolk across the world. Many local-level studies are subject to the attribution problems mentioned above, but Wellard et al. (2012) cautiously note a convergence of climate data with the perceptions of farmers and officials to the effect that over the last 30 years the rainfall in Malawi has become less predictable, that the rainy season is arriving later in the year causing delays in planting

Table 9-3 | Major demographic, poverty-related, economic, governance, and environmental trends in rural areas of developed and developing countries.

	Developed countries	Developing countries
Demographic trends	Rural population accounts for 22.3% of the total population (or about 276 million people) (UN-DESA Population Division, 2012). Rural areas account for 75% of land area in OECD countries (OECD, 2006). Rural population has peaked (absolute numbers) in Europe and North America. Rural depopulation in some places, but also counter-urbanization with people moving from urban to rural areas elsewhere.	Rural population accounts for 50.3% of the total population (or about 2.5 billion people) in less developed countries (excluding LDCs), 71.5% (or about 608 million people) in LDCs. Rural population has already peaked in Latin America and the Caribbean, East and Southeast Asia; expected to peak around 2025 in the Middle East, North Africa, South and Central Asia; around 2045 in sub-Saharan Africa.
Dependence on agriculture	Agriculture accounts for only 13% of rural employment in the EU (OECD, 2006), and less than 10% on average across developed countries; however, it has a strong indirect influence on rural economies. Increased competition as a result of economic globalization has resulted in agriculture no longer being the main pillar of the rural economy in Europe. Economic policies are primary drivers, with social re-composition and economic restructuring taking place (Marsden, 1999; Lopez-i-Gelats et al., 2009).	Proportion of rural population engaged in agriculture declining in all regions (Figure 9-2). Agriculture still provides jobs for 1.3 billion smallholders and landless workers (World Bank, 2008). Non-agricultural including labor-based and migration-based livelihoods increasingly existing alongside (and complementing) farm-based livelihoods. Agricultural initiatives and growth still important for adaptation and for smallholders in Africa and Asia (Collier et al., 2008; Osbahr et al., 2008; Kotir, 2011).
Poverty and inequality	Per capita gross domestic product (GDP) in rural areas of OECD countries is only 83% of national average (but significant variation within and between countries): driven by out-migration, aging, lower educational attainment, lower productivity of labor, low levels of public services (OECD, 2006).	Rates of poverty (percentage of population living on less than US$2 per day) and extreme poverty (percentage of population living on less than US$1.25 per day) falling in rural areas in most parts of the world; but rural poverty and rural extreme poverty rising in sub-Saharan Africa. Recent price hikes and volatility exacerbated hunger and malnutrition among rural households, many of which are net food-buyers (FAOSTATS, 2013). Hunger and malnutrition prevalent among rural children in South Asia and sub-Saharan Africa (World Bank, 2007; IFAD, 2010); see Figure 9-2 and Table 9-4.
Economic, policy, governance trends	Shift from agricultural (production) to leisure (consumption) activities; focus on broader amenity values of rural landscapes for recreation, tourism, forests, and ecosystem services (OECD, 2006; Rounsevell et al., 2006; Bunce, 2008). Agricultural subsidies under pressure from international trade negotiations and domestic budgetary constraints. As a result of recent price hikes, domestic price support has been lowered in OECD countries. New policy approach in OECD countries that focuses on investments and targets a range of rural economic sectors and environmental services.	Interconnectedness and economic openness in rural areas have encouraged shifts to commercial agriculture, livelihoods diversification and help knowledge transfers (Section 9.3.3). Interlinkages between land tenure, food security, and biofuel policies impact rural poverty (see Sections 7.1 and 7.2.2 for further details). Decentralization of governance and emergence of rural civil society. Movements toward land reform in some parts of Asia (Kumar, 2010). Emergence of economies in transition, characterized in places by coexistence of leading and lagging regions; political and democratic decentralization leading to increasing complexity of policy (World Bank, 2007).
Environmental degradation	Different socioeconomic scenarios have varying impacts on land use and agricultural biodiversity (Reidsma et al., 2006).	Resource degradation, environmentally fragile lands subject to overuse and population pressures, exacerbating social and environmental challenges. Multiple stressors increase risk, reduce resilience, and exacerbate vulnerability among rural communities from extreme events and climate change impacts (Section 13.2.6).
Rural-urban linkages and transformations	Changes in land use and land cover patterns at urban-rural fringe affected by new residential development, local government planning decisions, and environmental regulations (Brown, D.G. et al., 2008).	Stronger rural-urban linkages through migration, commuting, transfer of public and private remittances, regional and international trade, inflow of investment, and diffusion of knowledge (through new information and communication technologies) (IFAD, 2010). Continued out-migration to urban areas by the semiskilled and low-skilled, reducing the size of the rural workforce (IFAD, 2010). Trend for migration to small and medium-sized towns (Sall et al., 2010). Increased volumes of agricultural trade, growing by 5% on average (annually) between 2000 and 2008 (WTO, 2009). New initiatives of foreign direct investment (FDI) in agriculture in the form of large-scale land acquisitions in developing countries (World Bank, 2010; Anseeuw et al., 2012).

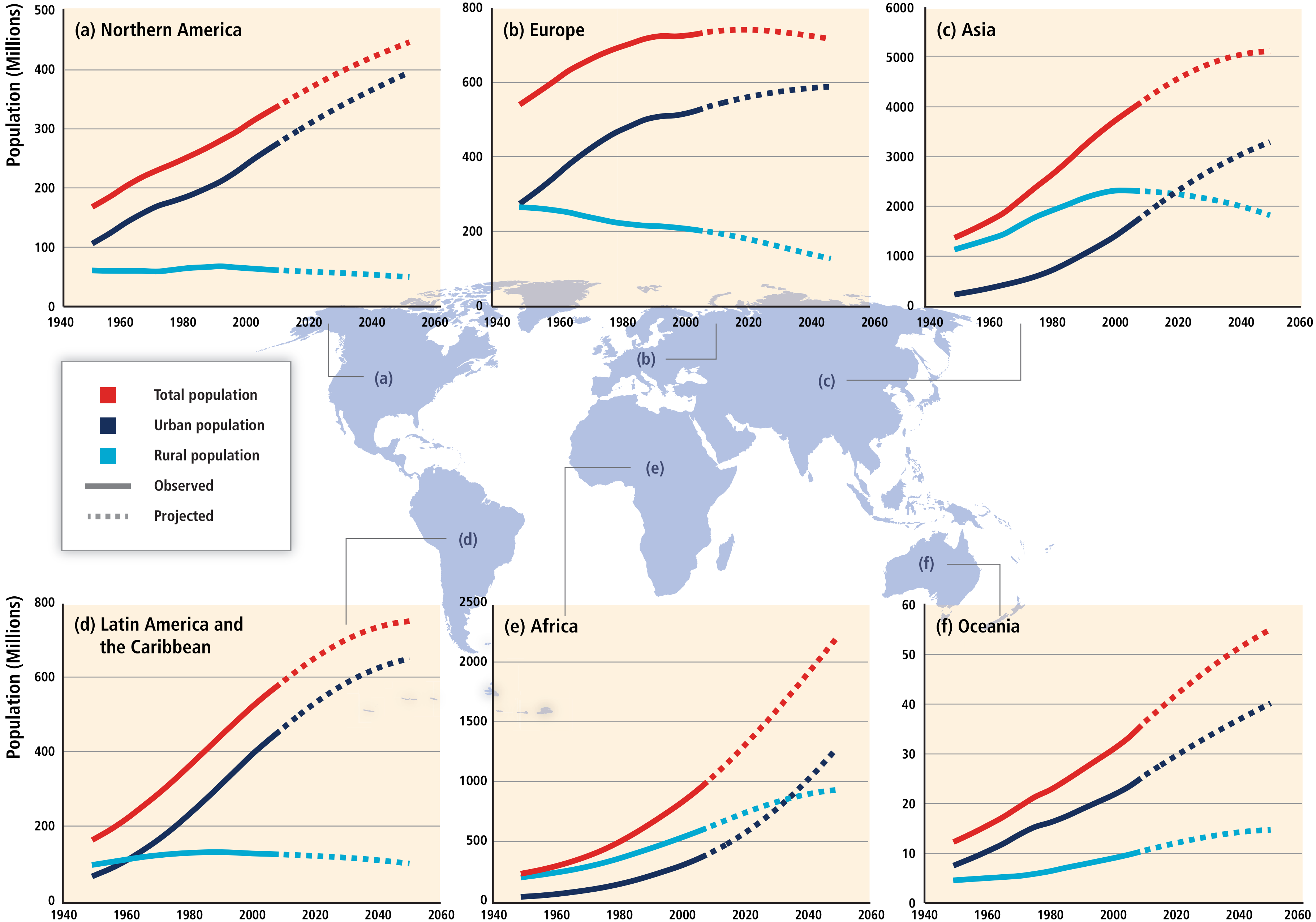

Figure 9-1 | Trends in rural, urban, and total populations by region; solid lines represent observed values and dotted lines represent projections (UN DESA Population Division, 2013). Note: Regions used in the source do not correspond with the IPCC regions covered in Chapters 22–30.

Table 9-4 | Poverty indicators for rural areas of developing countries. Source: Adapted from IFAD (2010).

	Incidence of poverty (%)		Incidence of rural poverty (%)		Incidence of extreme poverty (%)		Incidence of extreme rural poverty (%)		Rural people as % of those in extreme poverty	
	1988	2008	1988	2008	1988	2008	1988	2008	1988	2008
Developing world	69.1	51.2	83.2	60.9	45.1	27.0	54.0	34.2	80.5	71.6

Note: the incidence of extreme poverty and poverty is defined as percentage of people living on less than US$1.25 per day and less than US$2 per day, respectively.

of the main crops, and that damaging dry spells during the rainy season have become more frequent.

Glacial retreat in Latin America is one of the best evidenced current impacts on rural areas (see Section 27.3.1.1). In highland Peru there have been rapid observed declines since 1962 in glacier area and dry-season stream flow, on which local livelihoods depend, which accord well with local perceptions of changes that are necessitating adaptation (Orlove, 2009). Other studies of the area focus both on observed changes in water availability and on glacial lake outburst floods, which are attributable to climate change (Carey, 2010; Bury et al., 2011; Carey et al., 2012). There is also a rich specialized literature on the impacts of shrinking sea ice and changing seasonal patterns of ice formation and melt on indigenous peoples in the Arctic (Ford, 2009; Beaumier and Ford, 2010; see also Section 28.2.5.1.7).

Migration associated with weather-related extremes or longer-term climate trends is discussed in Table 12-3, with empirical examples of migrations linked to droughts, coastal storms, floods, and sea level rise. The Asian Development Bank (ADB, 2012) gives a figure of 42 million people displaced by extreme weather events in Asia and the Pacific over 2010–2011. Attribution of migration to climate change is extremely complex, as recognized by Black et al. (2011a), because life in rural areas across the world typically involves complex patterns of rural-urban and rural-rural migration, subject to economic, political, social, and demographic drivers, patterns that are modified or exacerbated by climate events and trends rather than solely caused by them (see also Section 12.4.1).

9.3.3. Future Impacts

This section examines the major impacts of climate change identified or projected for rural areas, under the headings of economic base and livelihoods; infrastructure; spatial and regional interconnections, including migration, trade, investment, and knowledge; and second-order impacts of climate policy. Section 9.3.4 assesses the literature on impact through a different and specific lens, that of economic valuation. The biophysical impacts of climate change on food crops are dealt with primarily in Chapter 7; but also here and in Section 9.3.4 insofar as they affect rural economies. Biophysical impacts on non-food cash crops are discussed below. As with the observed impacts in Section 9.3.2, the future impacts of climate change described here, and quantified in Section 9.3.4, are at the latter stages of complex causal chains that flow through changing patterns of extreme events and/or effects of climate change on biophysical processes in agriculture and less-managed ecosystems. Lal et al. (2011) show the regional specificity of projected socioeconomic impacts across the rural USA, with different regions affected through agriculture, water stress, and energy costs. Anderson et al. (2010) discuss the complexity of projected impacts across dryland regions of developing countries. These considerations increase the uncertainty associated with any particular impact on the economic base, on land use, or on regional interconnections.

9.3.3.1. Economic Base and Livelihoods

9.3.3.1.1. General considerations

Climate change will affect rural livelihoods, or "the capabilities, assets (stores, resources, claims, and access) and activities required for a means of living" (Chambers and Conway, 1992, p. 6). Many, though by no means all, rural livelihoods are dependent on natural resources (e.g., agriculture, fishing, and forestry), and their availability will vary in a changing climate. This will have effects on human security and well-being (Kumssa and Jones, 2010; see also Chapter 12). Climate change impacts on smallholder and subsistence farmers will be compounded by environmental and physical processes affecting production at a landscape, watershed, or community level; and other impacts, including those on human health and on non-agricultural livelihoods (Morton, 2007) and also trade and food prices (Anderson et al., 2010). Despite the growing importance of non-farm livelihoods in rural areas worldwide (Ellis, 2000; Reardon et al., 2007), and households pursuing interdependent agricultural and non-agricultural livelihoods in peri-urban areas as a risk management strategy (Lerner and Eakin, 2010; Lerner et al., 2013), there is a relative scarcity of literature on the interactions of these with climate variability and climate change.

Climate variability and change interacts with, and sometimes compounds, existing livelihood pressures in rural areas, such as economic policy, globalization, environmental degradation, and HIV/AIDS, as has been shown in Tanzania (Hamisi et al., 2012), Ghana (Westerhoff and Smit, 2009), South Africa (Reid and Vogel, 2006; Ziervogel and Taylor, 2008; O'Brien et al., 2009), Malawi (Casale et al., 2010), Kenya (Oluoko-Odingoa, 2011), Senegal (Mbow et al., 2008), and India (O'Brien et al., 2004). Economic heterogeneity of farm households within communities, in terms of farm and household size, crop choices, and input use, will be important in determining impacts (Claessens et al., 2012), as will social relations within households that affect production (Morton, 2007).

Projected impacts on yields and production of food crops are assessed in Section 7.4.1 and Figure 7-7. Local warming in excess of 1°C is projected to have negative impacts in both temperate and tropical regions without adaptation (though individual locations may benefit). There is *medium confidence* in large negative impacts of local increases of 3°C to 4°C, on productivity, production, and food security, globally and particularly in tropical countries, that go beyond adaptive capacity. The impacts of climate change on the agricultural sector in Africa, dominated by smallholder farming and very largely rainfed, are considered to be very significant to economies and livelihoods (Collier et al., 2008; Hassan, 2010; Kotir, 2011; Müller et al., 2011). These results emerge across a range of scenarios. Several other studies also map declines in net revenues from crops and the associated links with food security and poverty (Thurlow and Wobst, 2003; Reid et al., 2008; Molua, 2009; Thurlow et al., 2009).

Post-harvest aspects of agriculture—storage on-farm and commercially, handling, and transport—have been relatively neglected in discussions of climate change, but will be affected by changes in temperature, rainfall, humidity, and by extreme events. Many adaptation opportunities are

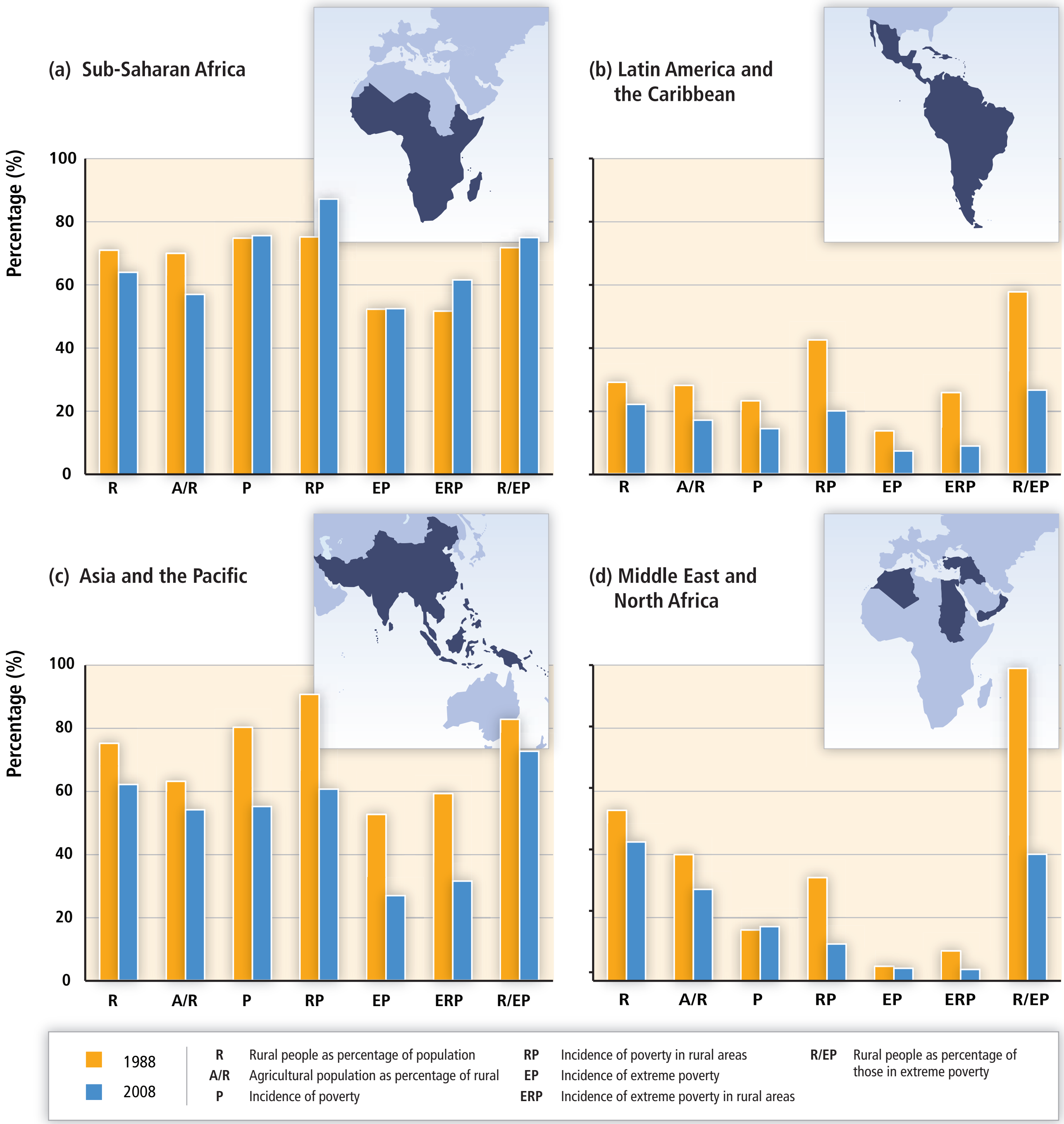

Figure 9-2 | Demographic and poverty indicators for rural areas of developing countries, by region (adapted from IFAD, 2010). Shaded countries are those for which data were available in the original source. Note: Regions used in the source do not correspond with the IPCC regions covered in Chapters 22–30.

already understood by post-harvest service providers, but getting post-harvest knowledge into use at scale is a significant challenge (Stathers et al., 2013; see also Tefera, 2012). Future impacts on production and storage will affect prices. Food crises in Africa triggered by moderate declines in agricultural production have been exacerbated by "exchange entitlement failures"—food price spikes and asset price collapses (Devereux, 2009). Rising food prices negatively affect many rural people who are net food buyers (see Table 7-1), and the poorest of the poor in rural areas—female-headed households (which tend to be poorer than male-headed households) and those who have limited access to land, modern agricultural inputs, infrastructure, and education (Ruel et al., 2010).

The remainder of this section discusses issues around climate impacts on agricultural livelihoods, other than food crop production: water as an input to agriculture, non-food crops, livestock, and fisheries.

9.3.3.1.2. Water

Water supply will be impacted through climate change (Chapter 3). In rural areas groundwater extraction and irrigation water availability is crucial for agricultural livelihoods but is typically not included in modeled projections of future crop yields, as discussed by Lobell and Field (2012). At the same time, non-climate trends including population growth and lack of adequate regulatory frameworks will greatly affect demand for water by agriculture and other competing uses, as discussed by Macdonald (2010) for the southwestern USA, by Juana et al. (2008) for South Africa, and by multiple authors for the Middle East (Iglesias et al., 2010; Chenoweth et al., 2011; Sowers et al., 2011; Hanafi et al., 2012; Rochdane et al., 2012; Verner, 2012).

At the continental level in Africa, analysis of existing rainfall and recharge studies suggests that climate change will not lead to widespread catastrophic failure of improved rural groundwater supplies, but it could affect a population of up to 90 million people, as they live in rural areas where annual rainfall is between 200 and 500 mm yr^{-1}, and where decreases in annual rainfall, changes in intensity, or seasonal variations may cause problems for groundwater supply (Macdonald et al., 2009). At higher resolution groundwater resources are threatened (e.g., in South Africa; Knüppe, 2011), and multiple water crises are expected to result from the increasing demand, further affecting people in rural areas (Nkem et al., 2011). Climate change is expected to impact water resources in the Asian region in a major way. Immerzeel et al. (2010), in a study of the Indus, Ganges, Brahmaputra, Yangtze, and Yellow River basins, conclude that different river basins would experience different impacts on water availability and food security due to climate change. They further argue that the Brahmaputra and Indus basins would be more susceptible to changes in water availability affecting the food security of 60 million people. In southern Europe, declines in rainfall and meltwater from glacial ice and snow would increase the costs of production and living (Falloon and Betts, 2010). Drought could threaten biodiversity and traditional ecosystems particularly in southern Europe, with problems exacerbated by declining water quality. Decline in economic activity may increase rural depopulation and harm the development of rural communities in southern Europe (Westhoek et al., 2006).

9.3.3.1.3. Non-food crops and high-value food crops

Non-food crops and high-value food crops, such as cotton, wine grapes, beverage crops, and other cash crops, which represent an important source of livelihood in many rural areas, have received less attention than staple food crops when assessing the impacts of climate change. Literature on biofuels such as jatropha focuses on the impacts of biofuels on climate change rather than on the effects of climate on yields and other relevant variables in these agricultural systems. Where crops have dual use as food and biofuel (e.g., oilseeds, sugarcane, sugar beet, maize, and wheat) impacts can be inferred from studies that focus on their use for food.

The findings of Easterling et al. (2007), that cotton yields would decrease as changes in temperature and precipitation overcome potential benefits of increasing carbon dioxide (CO_2), have been corroborated in other findings, such as those of Haim et al. (2008, p. 433) that cotton cultivation in Israel will decline by 52% and 38% by 2070–2100 under the SRES A2 and B2 scenarios, and that the net revenue will also decrease by 240% and 173% in both scenarios. Few systematic assessments have been done on other fiber crops such as jute, kenaf, and flax.

Climate change impacts on wine grapes have been extensively studied and documented. Climate impacts such as increasing number of hot days and decreasing frost risk may benefit some varieties. Lobell et al. (2006) assess the impacts of climate change on yields of six perennial crops in California by 2099, and report that the production of wine grapes will experience relatively small changes compared to other commodities during the concerned period. The uncertainty analysis shows the yield variations are limited within 10%, although Gatto et al. (2009) argue that the revenue of the industry in Napa, California, could decline by 2034. Jones et al. (2005) indicate that future climate change will exceed climatic thresholds affecting ripening for existing varieties grown at the margins of their climatic limits. Warmer conditions could also lead to more poleward locations becoming more conducive to grape growing and wine production.

Lobell and Field (2012) model impacts on 20 perennial crops in California under the A2 and B1 scenarios; of the four crops with the most reliable models cherry yields are projected to decline by nearly 20%, strawberries and table grapes to experience smaller declines, and almonds a slight positive trend. These projections do not incorporate adaptation options or possible decline in irrigation water supply, which would limit production. Yields of several cash crops in the Middle East such as olives, apples, and pistachios may decline if winter temperatures are too high (Verner, 2012).

The case of tropical beverage crops, in particular coffee, is discussed in Box 9-1, and projected changes in area suitable for all three tropical beverage crops are set out in Table 9-5.

9.3.3.1.4. Livestock

The impacts of climate change on livestock—which form a part of a variety of farming systems (Devendra et al., 2005)—are seen by Thornton et al. (2009) as a neglected research area complicated by other

9

Box 9-1 | Impacts of Climate Change on Tropical Beverage Crops

The major traded beverage crops coffee, tea, and cocoa support the livelihoods of several million small-scale producers in more than 60 countries of the tropics of Africa, Asia, and Latin America. Coffee production has long been recognized as sensitive to climate variability, with global production and prices sensitive to occasional frosts in Brazil—the world's largest producer (Varangis et al., 2003). Likewise the livelihoods of millions of small producers are dependent both on stability of production and stability in world prices. During the last crash in coffee prices from 2000–2003 poverty levels in the coffee growing regions of Nicaragua increased, while they fell in the rest of the country (World Bank, 2003); subsequently during the drought associated with El Niño in 2005 coffee productivity fell to between a third and half of normal, similarly leading to severely reduced income for small producers (Haggar, 2009).

Gay et al. (2006), analyzing the effects of recent climate change on coffee producing areas in Veracruz, Mexico, have developed econometric models of the relationship between coffee productivity and fluctuations in temperature and precipitation, which gave an R^2 of 0.69 against historical data. Extrapolating the historical tendencies in temperature and precipitation to 2020 and applying their econometric model, they predict that coffee production is *likely* to decline by 34%, and this decline in production takes producers from making net profits of on average around US$200 per acre to less than US$20 per acre. This has led to a series of studies projecting the effects of climate change on the distribution of Arabica coffee growing areas of the coming decades summarized below and in Table 9-5.

For Brazil, Assad et al. (2004) and Pinto et al. (2007) have mapped the changes in area suitable for coffee production in the four main coffee producing states. A 3°C increase in temperature and 15% increase in rainfall (taken from the general prediction of climate change for southern Brazil in the IPCC Third Assessment Report of 2001) would lead to major changes in the distribution of coffee producing zones. In the main coffee producing states of Minas Gerais and São Paulo the potential area for production would decline from 70 to 75% of the states to 20 to 25%, production in Gioas would be eliminated, but the area would be reduced only by 10% in Parana. New areas suitable for production in Santa Catarina and Rio Grande do Sul will only partially compensate the loss of area in other states (Pinto and Assad, 2008). The economic impacts of a rise in temperature of 3°C would cause a 60% decline in coffee production in the state of São Paulo equal to nearly US$300 million income (Pinto et al., 2007).

Models developed by CIAT predict the distribution of coffee under the A2A climate scenario using a statistical downscaling of the climate change data from 20 different General Circulation Models (GCMs) used in the IPCC Fourth Assessment. They use WorldClim data to characterize the current distribution of coffee using 19 climatic variables and then use the climate data downscaled to 1, 5, and 10 km resolution to map where those conditions may occur in the future (2020 or 2050). This method has been applied to coffee distribution in Kenya (CIAT, 2010), Central America, and Mexico (Laderach et al., 2010; Glenn et al., 2013); tea production in Kenya (CIAT, 2011a) and Uganda (CIAT, 2011b); and cocoa production in Ghana and Côte d'Ivoire (CIAT, 2011c; Laderach et al., 2013) (Table 9-5). The suitability for coffee crops in Costa Rica, Nicaragua, and El Salvador will be reduced by 40% (Glenn et al., 2013) while the loss of climatic niches in Colombia will force the migration of coffee crops toward higher altitudes by mid-21st century (Ramirez-Villegas et al., 2012). In the same way, increases in temperature will affect tea production, in particular at low altitudes (Wijeratne, et al., 2007). Only one similar study has been done for Robusta coffee (Simonett, 2006), in Uganda, which shows similarly drastic changes in both distribution and total area suitable for coffee production.

Effects are also expected on the incidence of pests and diseases in these crops. Increased generations under climate change for the coffee nematode have been predicted for Brazil (Ghini et al., 2008). Jaramillo et al. (2011) conclude that Coffee Berry Borer (*Hypothenemus hampei*) distribution in East Africa has expanded as a result of rising temperatures, and predicts, based on A2A and B2B scenarios of Met Office Hadley Centre climate prediction model 3 (HadCM3), that it will spread to affect the main coffee producing areas of Ethiopia, Kenya, Uganda, Rwanda, and Burundi by 2050.

Continued next page →

Box 9-1 (continued)

At a minimum climate change will cause considerable changes in the distribution of these crops, disrupting the livelihoods of millions of small-holder producers. In many cases the area suitable for production would decrease considerably with increases of temperature of only 2°C to 2.5°C. Although some local areas may experience improved conditions for coffee production, for example, high-altitude areas of Guatemala, the overall predictions are for a reduction in area suitable for coffee production by 2050 in all countries studied (Laderach et al., 2010).

drivers of change, rapid change in livestock systems, spatial heterogeneity, and social inequality between livestock keepers. They review various pathways of impact on livestock. Impacts through drought will be significant, as will heat stress, particularly of *Bos taurus* cattle. Impacts through animal health and disease will be even harder to predict than other categories of impact (Thornton et al., 2009). Franco et al. (2011) reveal significant declines in forage for ranching in California under SRES scenarios B1 and A2.

Pastoralists, who are dependent on livestock grazed in arid, semiarid, or mountainous areas, display very specific combinations of adaptive capacity, especially through mobility and vulnerability, as discussed in Section 9.3.5. Ericksen et al. (2012), with particular reference to East Africa, discuss possibilities of loss of rangeland productivity, changes in rangeland composition toward browse species, and changes in herd dynamics through more frequent droughts as possible impacts. In the Middle East, rangelands will be under substantial climate stress, which may reduce their carrying capacity, in light of the growing demand for meat products and the region's growing livestock population (Verner, 2012, p. 166). Little et al. (2001) discuss impacts of floods, directly and through disease, on pastoral herds. Similarly in the Ferlo Region in northern Senegal, modest reduction in rainfall of 15% in combination with a 20% increase in rainfall variability could have considerable effects on livestock stocking density and profits, reducing the optimal stocking density by 30%, based on six GCMs (Hein et al., 2009).

As extensive livestock production is associated with semiarid areas marginal for cropping, some authors project shifts toward livestock production under climate change. Modeled data from across Africa on the net income per unit of land from crops and different livestock species show that farmers are more likely to keep livestock, compared to crop cultivation, as temperatures increase and as precipitation decreases. Within livestock production, beef production will decline and sheep and goat production increase (Seo and Mendelsohn, 2007a). Large-scale commercial beef cattle farmers are most vulnerable to climate change, particularly because they are less likely to have diversified (Seo and Mendelsohn, 2007b). Kabubo-Mariara (2009) shows for non-pastoral areas of Kenya the nonlinear relationship of livestock production to climate change, whereby increased mean precipitation of 1% could reduce revenues from livestock by 6%. Jones and Thornton (2009) identify major transition zones across Africa where increased probability of drought up to 2050 will create conditions for shifts from cropping to livestock.

9.3.3.1.5. Fisheries

Impacts of climate change on aquatic ecosystems will have adverse consequences for the world's 36 million fisherfolk, through multiple pathways including changes in fish stock distribution and abundance, and destruction of fishing gear and infrastructure in storms and severe

Table 9-5 | Projected changes in areas suitable for production of tropical beverage crops by 2050.

Crop	Countries	Change in climate by 2050	Change in total area by 2050	Change in distribution by 2050 (in meters above sea level)
Coffee	Guatemala, Costa Rica, Nicaragua, El Salvador, Honduras, Mexico[6]	2.0–2.5°C increase in temperature 5–10% decline in total rainfall	Between 38% and 89% decline in area suitable for production	Minimum altitude suitable for production rise from 600 to 1000
	Kenya[1]	2.3°C increase in temperature Rainfall increase from 1405 mm to 1575 mm	Substantial decline in suitability of western highlands, some decline in area optimal for production in eastern highlands	Minimum altitude for production rise from 1000 to 1400
Tea	Kenya[2]	2.3°C increase in temperature Rainfall increase from 1655 mm to 1732 mm	Majority of western highlands lose suitability, while losses are compensated by gains at higher altitude in eastern highlands	Optimum altitude for production change from 1500–2100 to 2000–2300
	Uganda[3]	2.3°C increase in temperature Rainfall increase from 1334 mm to 1394 mm	Considerable reduction in suitability for production across all areas	Optimal altitude change from 1450–1650 to 1550–1650
Cocoa	Ghana, Côte d'Ivoire[4,5]	2.1°C increase in temperature No change in total rainfall	Considerable reduction in area suitable for production; almost total elimination in Ivory Coast without adaptation measures	Optimal altitude change from 100–250 to 450–500

Sources: [1]CIAT (2010); [2]CIAT (2011a); [3]CIAT (2011b); [4]CIAT (2011c); [5]Laderach et al. (2013); [6]Glenn et al. (2013). Projections use the SRES A2 scenario; the projection methodology is described in Box 9-1.

weather events (Badjeck et al., 2010; see also Sections 5.4.3.3, 6.4.1.1, 7.4.2, 30.6.2.1). An indicator approach (assessing climate change impacts together with the high share of fisheries as a source of income) showed that economies with the highest vulnerability of capture fisheries to climate change were in central and western Africa (e.g., Malawi, Guinea, Senegal, and Uganda), Peru and Colombia in northwestern South America, and four tropical Asian countries (Bangladesh, Cambodia, Pakistan, and Yemen) (Allison et al., 2009). In China, Japan, and South Korea, changes in climate and social systems could have a negative impact on fisheries, adversely affecting livelihoods and food security of the region (Kim, 2010).

9.3.3.2. Infrastructure

Assessments of the impacts of climate change on infrastructure take a general or urban perspective and do not focus on rural areas, though rural impacts can be inferred. River flooding and sea level rise will produce temporary loss of land and land activities, and damage to transportation infrastructure particularly on coastal areas (Kirshen et al., 2008), with specific evidence from North America (Hess et al., 2008). Flooding events may cause sediment transport and damage roads and bridges (Nearing et al., 2004) as well as affecting reservoir storing capacity. Importantly, in rural areas usually there are few alternatives once a road is blocked and that may increase vulnerability of rural areas when facing extreme hydroclimatological events that impact transportation infrastructure (NRC, 2008). Climate change will affect the operation of existing water infrastructures (Kundzewicz et al., 2008). Some documented impacts on dams, reservoirs, and irrigation infrastructure include reduction of sediment load due to reductions in flows (associated with lower precipitation), positively affecting infrastructure operation (Wang et al., 2007); impacts of climate variability and change on storage capacity that creates further vulnerability (Lane et al., 1999); and failures in the reliability of water allocation systems (based on water use rights) due to reductions of streamflows under future climate scenarios (Meza et al., 2012).

In Arctic Canada and Alaska, infrastructure built for very cold weather will deteriorate as the air and ground warm. Larsen et al. (2008) estimate, using the Atmosphere-Ocean General Circulation Model (AOGCM) intercomparison project and an A1B scenario, increases in public infrastructure costs of 10 to 20% through 2030 and 10% through 2080 for Alaska, amounting to several billion dollars, much of it to be spent outside of urban centers. Lemmen et al. (2008) reports that foundation fixes alone in the largely rural Northwest Territories could cost up to CAN$420 million, and that nearly all of northern Canada's extensive winter road network, which supplies rural communities and supports extractive industries which bring billions of dollars to the Canadian economy annually, is at risk (Furgal and Prowse, 2008) from a 2°C to 4°C change in ground surface temperatures, which would imply a cost of replacement with all-weather roadways of CAN$85,000 per kilometer, over several decades.

9.3.3.3. Spatial and Regional Interconnections

In both developing and developed countries, rural areas have been increasingly integrated with the rest of world. The main channels through which this rapid integration process takes place are migration (permanent and cyclical), commuting, transfer of public and private remittances, regional and international trade, inflow of investment, and diffusion of knowledge through new information and communication technologies (IFAD, 2010), as well as the spatial intermingling of rural and urban economic activities (see Box CC-UR).

9.3.3.3.1. Migration

It is difficult to establish a causal relationship between environmental degradation and migration (see Section 12.4.1). Many authors argue that migration will increase during times of environmental stress (e.g., Brown and Crawford, 2008; Afifi, 2011; Kniveton et al., 2011; Gray and Mueller, 2012), and will lead to an increase in abandonment of settlements (McLeman, 2011). Climate variability has been associated with rural-urban migration (Mertz et al., 2011; Parnell and Walawege, 2011). Another body of literature argues that migration rates are no higher under conditions of environmental or climate stress (Cohen, 2004; Brown, 2008; van der Geest and de Jeu, 2008; Tacoli, 2009; McLeman and Hunter, 2010; Black et al., 2011a,b; Foresight, 2011; Gemenne, 2011; van der Geest, 2011). For Tacoli (2009) the current alarmist predictions of massive flows of so-called "environmental refugees" or "environmental migrants" are not supported by past experiences of responses to droughts and extreme weather events, and predictions for future migration flows are tentative at best. Analogies with past migration experiences are used frequently in such studies (McLeman and Hunter, 2010). For example, in Ghana the causality of migration was established to be relatively clear in the case of sudden-onset environmental perturbations such as floods, whereas in case of slow-onset environmental deterioration, there was usually a set of overlapping causes—political and socioeconomic factors—that come into play (van der Geest, 2011). Similarly, a recent survey by Mertz et al. (2010) has argued that climate factors played a limited role in past adaptation options of Sahelian farmers. Given the multiple drivers of migration (Black et al., 2011a,b) and the complex interactions that mediate migratory decision making by individual or households (McLeman and Smit, 2006; Raleigh, 2008; Black et al., 2011a,b; Kniveton et al., 2011), the projection of the effects of climate change on intra-rural and rural-to-urban migration remains a major challenge.

9.3.3.3.2. Trade

Agricultural exports accounted for around one-sixth of world agricultural production in 2012, while this proportion was higher for some commodities such as oilseeds, sugar, and fish (OECD and FAO, 2013). Global agricultural exports grew at an average annual rate of 9% in 2000–2005 and 11% in 2005–2011 (WTO, 2013, pp. 63–72). Apart from a major price hike and high price volatility since 2007–2008, several structural and cyclical factors—such as droughts in major producers, expansion of area under biofuel crop production, financial speculation, export restrictions—have led to volatility and unpredictability in the trading environment (Chapter 7; see also Abbott, 2008; FAO, 2008; Cooke and Robles, 2009; Karapinar and Haberli, 2010; Schmidhuber and Matuschke, 2010; Timmer, 2010; Headey, 2011;Wright, B.D., 2011; Anderson and Nelgen, 2012; Nazlioglu, 2013). In the absence of extensive literature and reliable data on within-country trade, this section focuses on international trade in the specific context of climate change.

There is *limited evidence* and *medium agreement* that climate change will affect trade patterns and it will increase international trade volumes in both physical and value terms by altering the comparative advantage of countries and regions, and given its potential impacts on agricultural prices (Nelson et al., 2009b, 2010, 2013; Tamiotti et al., 2009). For example, simulation based results from variants of the National Center for Atmospheric Research (NCAR) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) climate models (A2 scenario) suggest that climate change might lead to increases in export volumes (of rice, wheat, maize, millet, sorghum, and other grains) from developed to developing countries by 0.9 million Mtonnes to 39.9 million Mtonnes by 2050. Higher export volumes are expected if future scenarios consider CO_2 fertilization effects, as they produce lower world prices than scenarios without CO_2 effects. Many regions including South Asia, East Asia and Pacific, Middle East, North Africa, and sub-Saharan Africa are projected to increase their imports substantially over this period (Nelson et al., 2009b, 2010).

The recent literature highlights the potential role of trade in adaptation to climate impacts on global crop yields, while cautioning policy makers about the possible negative consequences of increased trade (Verburg et al., 2009; Lotze-Campen et al., 2010; Huang et al., 2011; Schmitz et al., 2012). Importing food might help countries adjust to climate change-induced domestic productivity shocks and mitigate related welfare losses (Reimer and Li, 2009; Tamiotti et al., 2009). Countries might also capitalize on new export opportunities arising from higher achievable yields, for example in Argentina (Asseng et al., 2013), or increasing heterogeneity of climate impacts on yields in neighboring countries, for example in Tanzania (Ahmed et al., 2012). Increased trade would lower the cost of food and thus help alleviate food insecurity; however, if it is driven by an expansion of agricultural areas (especially to marginal land and to forests), it would also lead to negative environmental consequences in the form of loss of biodiversity, deforestation, and additional carbon emissions (Verburg et al., 2009; Lotze-Campen et al., 2010; Schmitz et al., 2012).

If climate change affects crop yields negatively, and results in increased frequency of extreme events (IPCC, 2012; see also Chapter 3), especially in low-income developing countries, the consequent short-term food deficits might need to be supplied, fully or partly, through food aid (Alderman, 2010). Hence food aid agencies, such as the United Nations World Food Programme, might face additional operational challenges (Barrett and Maxwell, 2006; Harvey et al., 2010). Local or regional procurement of food aid, targeted distribution of food, and safety net programs through direct income transfers could be part of an overall strategy to address climate-induced shocks to food security (see also Chapter 7) (Alderman, 2010; Harvey et al., 2010).

The potential impacts of climate change on agricultural trade and the role that trade could play in adaptation will inevitably depend on countries' trade policies. There is *medium evidence* and *medium agreement* that deepening agricultural markets through trade reform, improved market access, avoiding export controls, and developing institutional mechanisms to improve the predictability and the reliability of the world trading system as well as investing in additional supply capacity of small-scale farms in developing countries could help reduce market volatility and offset supply shortages that might be caused by climate change (Reimer and Li, 2009; Tamiotti et al., 2009; UNEP, 2009; Karapinar, 2011, 2012; Tanaka and Hosoe, 2011; Ahmed et al., 2012).

9.3.3.3.3. Investment

Climate change may also affect investment patterns in rural areas. On the one hand, countries, regions, and sectors that are expected to be affected adversely by climate change may have difficulty attracting investment. On the other hand, ecological zones that will become favorable as a result of climate change are expected to see increasing inflow of investment. The recent price hikes in agricultural commodities have led to new initiatives of foreign direct investment (FDI) in large-scale crop production (World Bank, 2010b; Anseeuw et al., 2012), with capital-endowed countries with high food imports investing in large production projects in low-income countries endowed with low-cost labor forces and land and water resources. Climate change will lead to similar investment patterns. However, there is a risk that these new investments might not be integrated into local structures and that local populations will become increasingly vulnerable as they lose access to vital assets such as land and water (Anseeuw et al., 2012).

9.3.3.3.4. Knowledge

Rural areas are increasingly exposed to diffusion of knowledge through migration, trade and investment flows, technology transfers, and improved communication and transport facilities (IFAD, 2010), although differentials on knowledge access and diffusion (e.g., access to high-speed Internet) between rural and urban areas remain, even in high-income countries. Future impacts of climate change on these channels of integration will affect the pace and intensity of knowledge transfers. If trade, migration, and investment flows will be intensified as a result of climate change, this will have a positive impact on knowledge transfer both from and to rural areas.

Traditional knowledge (TK) developed to adapt to past climate variability and change can both be affected by climate change and used and transformed in adaptation (Nyong et al., 2007). Ettenger (2012) discusses how seasonal hunting camps among the Cree of Northern Quebec that were the occasion for intergenerational knowledge transfer have been disrupted by changing bird migrations, while new technologies such as the Internet, GPS, and satellite phones have been integrated into livelihood strategies. Climate change-induced migration can threaten TK transfer (Valdivia et al., 2010; Gilles et al., 2013). Disaster management by central government may undermine decentralization efforts, disfavoring TK transfer (Dekens, 2008).

9.3.3.4. Second-Order Impacts of Climate Policy

Policy responses for mitigation and adaptation affect rural people and their livelihoods and environments. Working toward increasing energy

Frequently Asked Questions

FAQ 9.2 | What will be the major climate change impacts in rural areas across the world?

The impacts of climate change on patterns of settlement, livelihoods, and incomes in rural areas will be complex and will depend on many intervening factors, so they are hard to project. These chains of impact may originate with extreme events such as floods and storms, some categories of which, in some areas, are projected with *high confidence* to increase under climate change. Such extreme events will directly affect rural infrastructure and may cause loss of life. Other chains of impact will run through agriculture and the other ecosystems (rangelands, fisheries, wildlife areas) on which rural people depend. Impacts on agriculture and ecosystems may themselves stem from extreme events like heat waves or droughts, from other forms of climate variability, or from changes in mean climate conditions such as generally higher temperatures. All climate-related impacts will be mediated by the vulnerability of rural people living in poverty, isolation, or with lower literacy, and so forth, but also by factors that give rural communities resilience to climate change, such as indigenous knowledge, and networks of mutual support.

Given the strong dependence in rural areas on natural resources, the impacts of climate change on agriculture, forestry, and fishing, and thus on rural livelihoods and incomes, are *likely* to be especially serious. Secondary (manufacturing) industries in these areas, and the livelihoods and incomes that are based on them, will in turn be substantially affected. Infrastructure (e.g., roads, buildings, dams, and irrigation systems) will be affected by extreme events associated with climate change. These climate impacts may contribute to migration away from rural areas, though rural migration already exists in many different forms for many non-climate-related reasons. Some rural areas will also experience secondary impacts of climate policies—the ways in which governments and others try to reduce net greenhouse gas emissions such as encouraging the cultivation of biofuels or discouraging deforestation. These secondary impacts may be either positive (increasing employment opportunities) or negative (landscape changes, increasing conflicts for scarce resources).

supply from renewable resources may result in landscape changes (Dockerty et al., 2006; Prados 2010); increasing employment opportunities (del Río and Burguillo, 2008); or increasing conflicts for scarce resources, such as water (Gold and Bass, 2010; Blair et al., 2011; McIntyre and Duane, 2011; Phadke, 2011). Planning applications for wind energy schemes in the UK have been subject to local opposition when they are perceived as having negative impacts on rural landscape qualities (van der Horst, 2007; Wolsink, 2007; Jones and Eiser, 2010). Governance of energy distribution is thus an important issue (Vermeylen, 2010; Devine-Wright, 2011). Steps toward energy self-sufficiency can reinforce rural autonomy in isolated rural communities, including indigenous groups (Love and Garwood, 2011).

Social responses to such changes are expected (Molnar, 2010). The promotion of biofuel crops has been an extremely controversial issue during 2000–2010, as they have potential socioeconomic impacts related to their asserted ability to act as stimulus for rural economies, promote changes in land ownership, and affect food security (German et al., 2011). Delucchi (2010) concludes that biofuels produced from intensive agriculture will aggravate stresses on water supplies, water quality, and land use, and impact rural areas (through land use change) and agriculture (see also Box CC-WE). Concerns about the impact of biofuel production on food security relates to increases in food prices, land concentration (and landgrabs), and competition for water (Eide, 2008; Müller et al., 2008; German et al., 2011). Gurgel et al. (2007), who modeled potential production and implications of a global biofuels industry by the end of the century under a reference scenario and a high-mitigation scenario, recognized the need for a high land conversion rate to achieve moderate objectives. Delucchi (2010) suggests developing biofuels programs with low inputs of fossil fuels and chemicals, that do not require irrigation, and on land with little or no economic or ecological opportunity cost (Plevin et al., 2010). This implies analyzing each case in its context, including production for both local and global markets, and factoring in concerns for social, cultural, and economic costs of biofuel production (i.e., impact of biofuel production on indigenous livelihoods and culture).

International mechanisms for emission reduction through forest and land management have been developed under the global initiative Reducing Emissions from Deforestation and Forest Degradation (REDD), now REDD+. These mechanisms are designed to use market tools (e.g., payment for ecosystem services) to reduce emissions, while providing social co-benefits following the principles of effectiveness, efficiency, and equity (Brown, D. et al., 2008; Hall, 2012; Hoang et al., 2013). However, there have been many criticisms that the rural poor are excluded from participation (Campbell, 2009; Sikor et al., 2010; van Noordwijk et al., 2010; Hall, 2012); and that lack of community participation can undermine a general decentralization of forest management (Phelps et al., 2010).

9.3.4. Valuation of Climate Impacts

This section assesses studies that have adopted various economic methods for valuation of impacts of climate change on rural areas. This is a difficult task and should reflect the significance of the ecological service categories for different stakeholders, including women (Kennet, 2009) and minority groups, and ideally the valuations of unit changes in the levels of those services across management options. Valuations can be made at individual or communal levels (Farber et al., 2006) and often involve complexities with regard to the use of social discount rates for comparing intergenerational effects over varying time horizons (Dasgupta, 2011). Different understandings of value, and different philosophical approaches to address it, may exist (Weisbach and Sunstein, 2008; Kosoy and Corbera, 2010; Spangenberg and Settele, 2010), which makes it more difficult to agree on valuation methodologies. The impacts of climate change are expected to be unequally distributed across the globe, with developing countries at a disadvantage, given their geographical position, low adaptive capacities (Stern, 2007; World Bank, 2010a) and the significance of agriculture and natural resources to the economies and people (Collier et al., 2008; World Bank, 2010a). Both direct and indirect impacts have been projected, such as lower agricultural productivity, increase in prices for major crops, and rise in poverty (Hertel et al., 2010), which have implications for rural areas and rural communities. This section discusses the valuation of impacts with reference to agriculture, fisheries and livestock, water resources, mining, extreme weather events and sea level rise, recreation, tourism, and forestry. There are various channels through which changes in economic values may occur in rural areas, such as through changes in profitability, crop and land values, and loss of livelihoods of specific communities through changes in fisheries and tourism values. Losses and gains in health status and nutrition, and wider economy-wide impacts such as changes in job availability and urbanization, also impact economic values that accrue to rural communities, the opportunities and the constraints that rural communities experience, and changes that rural landscapes undergo. Because rural areas are included, but not exclusively dealt with in calculations of economy-wide gross domestic product (GDP) losses due to climate change impacts, these are not dealt with separately in this chapter. Studies on the health impacts of climate change for the most part do not distinguish between rural and urban areas, although there are specific vulnerabilities that communities in rural areas face arising from a variety of factors such as remoteness, lack of access to services, and dependence on certain occupations such as farming which are dealt with in Section 11.3. The impact on availability of freshwater resources is another major area of concern for the developing regions in particular. Climate change can adversely impact poverty through multiple channels (Sections 10.9, 13.2).

Viewing impacts regionally, despite the ongoing debates around the uncertainty and limitations of valuation studies, scholars generally agree that some African countries could experience relatively high losses compared to countries in other regions (Collier et al., 2008; Watkiss et al., 2010; World Bank, 2010a). These conclusions emerge across a range of climate scenarios and models used by researchers. For instance, Watkiss et al. (2010) use the FUND model for a business-as-usual scenario and a scenario of mitigation to 450 ppm and 2°C global mean temperature increase as generated by the PAGE2002 model, while the World Bank uses a range of country specific models for calculating costs. Global costs including adaptation costs are calculated for an approximately 2°C warmer world by 2050 for Mozambique, Ethiopia, Ghana, Bolivia, Vietnam, Samoa, and Bangladesh. Overall negative consequences are seen for Africa and Asia, due to changes in rainfall patterns and increases in temperature (Müller et al., 2011). Though climate change and climate variability would impact a range of sectors, water and agriculture are expected to be the two most sensitive to climatic changes in Asia (Cruz et al., 2007; see also Chapter 3) and for droughts in particular for Australia (Meinke and Stone, 2005; Nelson et al., 2007). In Latin American and Caribbean countries, higher temperatures and changes in precipitation patterns associated with climate change affect the process of land degradation, compromising extensive agricultural areas. Research on climate change impacts in rural North America has largely focused on the effects on agricultural production and on indigenous populations, many of whom rely directly on natural resources. Developed countries in Europe will be less affected than the developing world (Tol et al., 2004), with most of the climate sensitive sectors located in rural areas.

Valuation and costing of climate impacts draw upon both monetary and non-monetary metrics. Most studies use models that estimate aggregated costs or benefits from impacts to entire economies, or to a few sectors, expressed in relation to a country's GDP (Stage, 2010; Watkiss, 2011). Values that are aggregated across sectors generalize across multiple contexts and could mask particular circumstances that could be significant to specific locations, while expressing outcomes in aggregated GDP terms. This is a matter of concern for economies in Africa and Asia, where subsistence production continues to play a key role in rural livelihoods. Valuation of non-marketed ecosystem services poses further methodological and empirical concerns (Dasgupta, 2008, 2009; Stage, 2010; Watkiss, 2011). Würtenberger et al. (2006) developed a methodology to estimate environmental and socioeconomic impacts of agricultural trade regarding virtual land use, and Adger et al. (2011) use qualitative methodologies to consider non-market metrics of risk, focusing on place- and identity-based principles of justice, which recognize individual and community identity in decision making.

Integrated assessment models and cost-benefit tools have been criticized: for being inadequate to assess intergenerational events, or processes with high levels of uncertainty and irreversibility; for not considering equity concerns and power structures; for assigning monetary values on the basis of incomplete information or assuming speculative judgments regarding the monetary value of, for example, natural resources (Kuik et al., 2008; Ackerman et al., 2009); and for not recognizing incommensurability (Aldred, 2012). In recent years, various perspectives for valuing the economic impacts of climate change have come into focus including the feminist (Nelson, 2008; Power, 2009), deliberative (Zografos and Howarth, 2010), or behavioral economics-based (Brekke and Johansson-Stenman, 2008; Gowdy, 2008), and the integration of economics with moral and political philosophy (Dietz et al., 2008). Some common characteristics of these new approaches include interdisciplinarity, acknowledging the diversity of views, and maintaining complexity in models. Research in this area, although relatively recent, shows promise. Illustrative regional and sub-regional estimates for the value of agricultural and non-agricultural impacts of climate change, as available in the literature, are presented here.

9.3.4.1. Agriculture

Changes in agricultural production will have corresponding impacts on incomes and well-being of rural peoples. The largest known economic impact of climate change is on agriculture because of the size and sensitivity of the sector, particularly in the developing world and to a lesser extent in parts of the developed world. A large number of studies to evaluate the impacts on the agricultural sector and its ramifications for communities have been conducted at various scales, ranging from micro-level farm models to large-scale regional and country level climate cum socioeconomic scenario modeling exercises. Some of these also report values for associated economic losses.

Since models are simplifications of complex real-world phenomena, different models tend to highlight different aspects of impacts and their consequent economic values. For instance, in estimating economic losses the Ricardian method has been used widely to study climate change impacts (with adaptation inbuilt) in agriculture. However, often such analysis does not incorporate features like technological progress, relative price changes, agricultural policy, and other dynamic characteristics. Similarly on the biophysical impacts side, changes in the El Niño-Southern Oscillation (ENSO) statistics may also have serious economic implications for the agricultural sector in certain countries such as in Latin America and Australia (Kokic et al., 2007). However, ENSO responses differ strongly across climate models, and at the current stage of understanding do not allow conclusions to be drawn on how global warming will affect the Tropical Pacific climate system (Latif and Keenlyside, 2009). A sample of the available studies is provided in Table 9-6.

9.3.4.2. Other Rural Sectors: Water, Fisheries, Livestock, Mining

The changes in valuation of water resources due to climate change arise from expected impacts on populations dependent on these water resources and these will be felt in several parts of the world (Sections 3.4.9, 3.5, 3.8). Monetary estimates of losses due to impacts on water resources are not generalizable. Among alternative approaches to value water resources, use of the water footprint tool (Hoekstra and Mekonnen, 2012), which measures human utilization of water by a nation, and the concept of virtual water have been suggested for informing policy makers in water-scarce countries, such as Egypt.

Analysis of intergenerational valuation has provided some interesting results in valuation of marine fisheries (Ainsworth and Sumaila, 2005). For fisheries in rural coastal areas, some of the challenges faced include the valuation of environmental externalities such as breeding habitats, or mangroves, that might be lost due to climate change or other forces (Hall, 2011). It has also been argued that the true worth of livelihoods dependent on fisheries in developing countries, where these constitute part of a diversified livelihood or subsistence strategy, requires a different set of metrics from those used in the developed world (Mills et al.,

Table 9-6 | Illustrative sample of studies on economic value and changes in value from climate change impacts in the agriculture sector.

Findings and estimates	Country/region and model/scenario	Study
Annual economic loss in rice production: $54.17 million	Malaysia (2°C rise in temperature)	Vaghefi et al. (2011)
GDP reduction from loss of agricultural productivity by 2080: 1.4%; welfare loss: 1.7%	Southeast Asian countries: Thailand, Vietnam, Philippines, Singapore, Malaysia, Indonesia (dynamic CGE)	Zhai and Zhuang (2009)
Decline in food grain production between 2030 and 2050 by up to 18%	India (SRES A1B scenario)	Dasgupta et al. (2013)
Annual spending for coping with adverse agricultural impacts between 2010 and 2050: US$4.2–5 billion	Asia (various scenario based estimates)	ADB and IFPRI (2009)
Decline in farmland values for each degree Celsius of warming: 4–6000 pesos	Mexico (Ricardian analysis)	Mendelsohn et al. (2010)
Fall in crop land values for rural communities: 13%	USA (10% average increase in temperature)	Mendelsohn et al. (2007)
Mixed effects with some improved profits	Canada (increasing precipitation)	Mendelsohn and Reinsborough (2007)
Adverse impacts on farming	USA (increasing temperature)	Mendelsohn and Reinsborough (2007)
Crop losses under drought: CAN$7–171 per hectare	Canada (Canadian Global Model 2)	Wittrock et al. (2011)
Annual agricultural losses up to $3 billion Flooding increases losses	California (SRES B1 (low emissions) and SRES A2 (medium emissions) scenarios)	Franco et al. (2011)
Damages to agriculture, hydropower, and infrastructure (including coastal areas) by 2050: US$7.6 billion	Mozambique (dynamic CGE model)	World Bank (2010a)
Decline in gross domestic product (GDP) from agriculture and linked sectors: 10% from benchmark levels	Ethiopia (Cline, CGCM2, and PCM)	Mideksa (2010)
By 2100: total losses of US$48.2 billion to gains of US$90 billion In 2020 for 1.6% warmer and 3.7% drier climate: net farm revenues decline by up to 25%	11 African countries (Ricardian analysis; various climate scenarios)	Dinar et al. (2008)
Decline in daily per capita calorie availability by up to 10% in 2050	Developing countries (SRES A2 scenario; CSIRO and NCAR models)	Nelson et al. (2009)
Losses in gross value of production up to 25% (Guatemala, followed by other countries)	Guatemala, Belize, Costa Rica, Honduras (SRES A2 and B2; Regional climate models)	UN ECLAC (2010a,b)
Loss in incomes of farmers by 2020: 14%; by 2060: 20%	South America (SRES A1; Canadian Climate Centre)	Seo and Mendelsohn (2008)
Annual damages between 1% and 39% in farm property values	Brazil (climate predictions from 14 GCMs)	Sanghi and Mendelsohn (2008)
Varying impacts across regions; declining agricultural crop productivity in some	Southern Europe (IPCC AR4 climate projections; qualitative assessment)	Falloon and Betts (2010)
Large variation in impacts on crops in Europe by 2050, mostly negative	Most affected: Hungary, Serbia, Bulgaria, Romania (expert evaluation; climate predictions from RCMs)	Olesen et al. (2011)

Notes: CGCM2 = Coupled General Circulation Model 2; CGE = Computable General Equilibrium; CSIRO = Commonwealth Scientific and Industrial Research Organisation; GCM = General Circulation Model; NCAR = National Center for Atmospheric Research; RCM = Regional Climate Model; SRES = Special Report on Emission Scenarios.

2011). Climate change can also have significant impacts on livestock production (Section 9.3.3.1).

A relatively less researched area which may impact the livelihoods of rural communities is mining (Section 26.11.1.2). Economic viability of mining enterprises as well as communities dependent on them is vulnerable to climate change. Pearce et al. (2011) highlight concerns for Canada, where mining is a rural activity with few other available economic activities while Damigos (2012) finds economic losses for mining in the Mediterranean region and Greece in particular. Current and past infrastructure for mines was built under a no-climate change presumption and economic and ecological vulnerabilities as a result are substantial, and industry actors are unprepared to deal with this. There is little research on impacts in mining sectors in the USA and Mexico. Changes in the energy and water sector present a complex mix of risks and opportunities for primary extraction and processing industries. Site management, transport of supplies and resources to and from mines, exploration activities, and their associated costs would determine the extent of loss, along with the importance of the sector in the local economy (Backus et al., 2012).

9.3.4.3. Extreme Weather Events, Sea Level Rise

The climate change-related extreme events that may cause changes in economic values in rural areas include heat waves and droughts, storms, inundation, and flooding (Stern, 2007; Handmer et al., 2012; see also Section 3.4.9). A detailed discussion on the costs of climate extremes and disasters is set out by Handmer et al. (2012). Costs can be of two kinds: losses or damage costs and costs of adaptation. While some of the costs lend themselves to monetary valuation (such as infrastructure costs), others cannot be easily estimated such as the value of lives lost and the value of ecosystem services lost (for discussion on the methodologies for valuing costs refer to Handmer et al., 2012; see also Section 4.5.3).

Damage costs of floods and droughts (Section 10.3.1) and from sea level rise in Europe (Swiss Re, 2009) demonstrate the cost implications for rural communities in the developed regions of the world. Studies mapping the adverse impacts in UK and elsewhere in Europe show a range of sectors that are impacted in rural areas particularly due to drought in Europe and flooding in UK, with the worst effect being on summer crops in Mediterranean regions (Giannakopoulos et al., 2009). Longer term adaptation could reduce the severity of losses but could include displacement of agricultural and forestry production from southern Europe to the North. The UK Government's Foresight Programme (Foresight, 2004) estimates that global warming of 3°C to 4°C could increase flood damage costs from 0.1% up to 0.4% of GDP. Much of the investment in flood defenses and coastal protection would be in rural coastal areas.

Several studies from the developing countries provide evidence on the substantial costs rural communities in particular face in these countries. Salinity and salt water intrusion have implications for rural livelihoods as they impact both fisheries and agriculture (Section 5.5.3). Sea level rise also leads to wetland loss and coastal erosion. A few illustrations of the range of impacts of relevance for the rural economy are provided here. Loss of agricultural land and changes in the saline-freshwater interface is estimated to impact the economies of Africa adversely (Dasgupta, S. et al., 2009; SEI, 2009). Ahmed et al. (2009) suggest that climate volatility from increase in extreme events increases poverty in developing countries, particularly Bangladesh, Mexico, Indonesia, and countries in Africa. They also find that on simulating the effect of climate extremes on poverty in Mexico using the A2 scenario as generated by a Coupled Model Intercomparison Project Phase 3 (CMIP3) multi-model data set, rural poverty increases by 43 to 52% following a single climate shock due to climate extremes. Studying extreme events, Boyd and Ibarrarán (2009) use a CGE model to simulate the effects of persistent droughts on the Mexican economy and find declines in production of 10 to 20% across a variety of agricultural sectors between 2005 and 2026. Scenario-based stakeholder engagement has been tested for coastal management planning under climate change threats (Tompkins et al., 2008) and to determine impacts and responses of extreme events in coastal areas (Toth and Hizsnyik, 2008).

9.3.4.4. Recreation and Tourism; Forestry

Studies assessing the changes in economic value of recreation and tourism due to climate change are relatively fewer in number (coastal tourism is discussed in Section 5.4.4.2). Both sensitivity to climate variability and climate change have been considered in the literature. While some studies locate an increase in values for certain regions others estimate shifts in tourism and losses (Hamilton et al., 2005; Bigano et al., 2007; Beniston, 2010). Methodological challenges and contrasting findings for the short and long run pose problems in generalizing findings (economic values for recreation and tourism are discussed in Section 10.6). Change in economic values will impact rural communities (Lal et al., 2011), with the linkages between biodiversity, tourism, and rural livelihoods and rural landscapes being an established one both for developing and developed countries (Scott et al., 2007; Collins, 2008; Wolfsegger et al., 2008; Hein et al., 2009; Nyaupane and Poulde, 2011).

It has been argued that climate change would have adverse impacts on various ecosystems, including forests and biodiversity in many regions of the world (Preston et al., 2006; Stern, 2007; Eliasch, 2008; ADB, 2009; Ogawa-Onishi et al., 2010; Tran et al., 2010) and these will have implications for rural livelihoods and economies (Fleischer and Sternberg, 2006; Safranyik and Wilson, 2006; Chopra and Dasgupta, 2008; Kurz et al., 2008; Walton, 2010). However, monetary valuation of changes in non-marketed ecosystem services due to climate change continues to pose a challenge to researchers. To overcome some of the limitations, multi-criteria analysis has been used for forest management (Fürstenau et al., 2007).

9.3.5. Key Vulnerabilities and Risks

9.3.5.1. Drivers of Vulnerability and Risk

Discussions on climate vulnerability in rural areas must recognize competing conceptualizations and terminologies of vulnerability, particularly those of "starting point" and "end-point" vulnerability (O'Brien et al., 2007). The focus here is on starting point vulnerability, or contextual vulnerability (see Glossary and Chapter 19), while we consider risk to be the probability of adverse impact resulting from exposure and vulnerability (see Chapter 19). These distinctions are important because they can result in contradictory findings regarding vulnerability in rural areas, and the policy prescriptions derived therefrom are also different.

There is *low agreement*, but *medium evidence*, on the direction in which some key factors may affect vulnerability or resilience in rural areas, including rainfed as opposed to irrigated agriculture, small-scale and family-managed farms, integration into world markets, and diversification. Brouwer et al. (2007), contrary to expectations, found that vulnerability to flooding in Bangladesh in terms of damage suffered was lower for households that fully depended on natural resources than those who did not. Osbahr et al. (2008) found that diversification in rural areas does not always reduce vulnerability and can increase inequity within communities if it is not accompanied by reciprocity. There is *robust evidence* and *high agreement* on the importance for resilience of drivers such as access to land and natural resources, flexible local institutions and knowledge and information, and the association of gender and vulnerability (see Box CC-GC and Chapter 13).

The most commonly used approaches to analyzing causes of vulnerability use the concepts of entitlements or livelihoods in evaluating the multi-scale factors shaping people's assets, as well as their adaptive capacity to hazards and stressors. Although vulnerability is experienced locally, its causes and solutions occur at different social, geographic, and temporal scales, and are seen as context dependent (Ribot, 2010). Non-climate factors affecting vulnerability in rural areas at both individual and community levels (Eakin and Wehbe, 2009) include the following:

- Physical geography, for example, desert or semi-desert conditions (Lioubimtseva and Henebry, 2009), remoteness (Horton et al., 2010), level of dependence on climate conditions (Brondizio and Moran, 2008; Sietz et al., 2011)
- Economic constraints and poverty (Macdonald et al., 2009; Mertz et al., 2009a; Ahmed et al., 2011; Sietz et al., 2011)
- Gender inequalities (Nelson et al., 2002)
- Social, economic, and institutional shocks/trends (e.g., urbanization, industrialization, prevalence of female-headed households, landlessness, short-time policy horizons, low literacy, high share of agriculture in GDP), as well as demographic changes, HIV/AIDS, access to and availability of food, density of social networks, memories of past climate variations, knowledge, and long-term residence in the region (Parks and Roberts, 2006; Brondizio and Moran, 2008; Cooper et al., 2008; Macdonald et al., 2009; Mertz et al., 2009a; Simelton et al., 2009; Gbetibouo et al., 2010b; Ruel et al., 2010; Sallu et al., 2010; Ahmed et al., 2011; Mougou et al., 2011; Seto 2011).

This section focuses on the following drivers of vulnerability to climate change: water, market orientation and farm scale, institutions and access to resources, gender, migration, and access to information and knowledge.

9.3.5.1.1. Access to water

Reducing vulnerability requires a reduction of the multiple non-climate-related pressures on freshwater resources (e.g., water pollution, high water withdrawals) together with improvement of water supply and sanitation in developing countries (Kundzewicz et al., 2008). Water supply will be adversely affected by climate change, but vulnerability of populations will also be determined by other elements, such as the role of institutions in facilitating the access to water, or people's demand, which in turn is influenced by local cultural norms (Wutich et al., 2012) and perceptions of vulnerability which may differ between men and women (Larson et al., 2011). Improvements in technologies can reduce the perception of water scarcity and increase water demand without reductions in underlying vulnerability (El-Sadek, 2010; Sowers et al., 2011). Where appropriate water management institutions exist and are effective, their role in improving rural livelihoods has been demonstrated, for example in Tanzania's Great Ruaha basin (Kashaigili et al., 2009).

Past research has tended to agree that rainfed agriculture is more vulnerable to climate change (Bellon et al., 2011) and that irrigation is needed to decrease that vulnerability (Gbetibouo et al., 2010a). More recent findings suggest that this is context dependent and irrigation has been found to increase vulnerability in certain cases (Eakin, 2005; Lioubimtseva and Henebry, 2009). Cooper et al. (2008) concluded that in rainfed sub-Saharan Africa the focus should be on improving productivity of rainfed agriculture instead of irrigation as irrigation schemes are also being threatened by drought, and Ahmed et al. (2011) emphasize the role of drought-tolerant crops.

9.3.5.1.2. Market orientation and farm scale

Some authors argue that opening markets to international trade increases vulnerability of small farmers and poor people. However, linkages among international, regional, and local markets are not clear, including how global prices affect regional and local prices in the long term (Ulimwengu et al., 2009). Market integration is seen as reducing the capacity of indigenous or smallholder systems for dealing with climate risk in Bolivia (Valdivia et al., 2010), Honduras (McSweeney and Coomes, 2011), Mexico (Eakin, 2005), Mozambique (Eriksen and Silva, 2009; Silva et al., 2010), and in the Sahel (Fraser et al., 2011) by variously accelerating socioeconomic stratification and reducing crop diversity. On the other hand, distance from large markets is seen as increasing vulnerability of rainfed mixed crop/livestock areas in sub-Saharan Africa (Jones and Thornton, 2009) and the Peruvian Altiplano (Sietz et al., 2011). Each case needs to be analyzed within its complexity, considering interactions among all the factors that can affect vulnerability (Rivera-Ferre et al., 2013a).

Regarding the scale of farms, some authors suggest that small-scale farming increases the vulnerability of communities in rural areas (Gbetibouo et al., 2010b; Bellon et al., 2011) although their resilience (stemming from factors such as indigenous knowledge, family labor, livelihood diversification) should not be underestimated. Brondizio and Moran (2008) indicate that small farmers are less vulnerable than large, monocrop farmers when climatic variations make an area inappropriate for a particular crop, because they tend to cultivate multiple crops and work with on-farm biodiversity. However, they recognize that small farmers tend to suffer from technological limitations, low access to extension services, and market disadvantages.

9.3.5.1.3. Institutions, access to resources, and governance

Institutions and networks can affect vulnerability to climate change: through distribution of climate risks between social groups; by determining the incentive structures for adaptation responses; and by mediating external interventions (e.g., finances, knowledge and information, skills training) into local contexts (Agrawal and Perrin, 2008; Ribot, 2010). Institutions can decrease vulnerability (Anderson et al., 2010) or increase it (Eakin, 2005). Governance structures and communication flows as shown in a Swiss mountain region vulnerable to climate change (Ingold et al., 2010) and the knowledge and perceptions of decision makers are also important. Romsdahl et al. (2013) show that local government decision makers in the U.S. Great Plains resist seeing climate change as within their responsibilities, which has contributed to low levels of planning for either adaptation or mitigation, and thus to greater vulnerability, but that a reframing of issues around current resource management priorities could allow proactive planning.

Lack of access to assets, of which land is an important one, is accepted to be an important factor increasing vulnerability in rural people (McSweeney and Coomes, 2011). The breakdown of traditional land tenure systems increases vulnerability, particularly for those who experience poorer land access as a result (Brouwer et al., 2007; Dougill et al., 2010; Fraser et al., 2011). Those who benefit, for example, wealthier farmers who increased their landholding after privatization in Botswana, remain less vulnerable (Dougill et al., 2010).

9.3.5.1.4. Migration

The relationship of vulnerability to migration is complex. Areas of out-migration can experience reduced vulnerability if migrants send remittances, or increased vulnerability if the burden of work, usually for women, also increases. The decline in transmission of traditional knowledge through social networks can also increase vulnerability (Valdivia et al., 2010). Furthermore, those places receiving migrants can experience an excessive demographic growth, which increases pressure over scarce resources, as is being experienced in the semiarid tropics (Cooper et al., 2008; Obioha, 2008). Brondizio and Moran (2008) found that in-migration in the Amazon brought people with knowledge that is ill-adapted to the local environment (see Section 12.4).

9.3.5.1.5. Gender

Box CC-GC sets out the general issues on climate change and gender-related inequalities. These are of special relevance to rural areas, particularly but not solely in the developing world (Nelson and Stathers, 2009; Vincent et al., 2010; Alston, 2011) (*robust evidence*, *high agreement*). Access to land shows strong differences between men and women, as do labor markets (FAO, 2010), and access to non-farm entrepreneurship (Rijkers and Costa, 2012). Fewer than 20% of the world's landholders are women, but women still play a disproportionate role in agriculture. On average women make up around 43% of the agricultural labor force in developing countries; in South Asia almost 70% of employed women work in agriculture, and more than 60% in sub-Saharan Africa (FAO, 2010, 2011). Climate change also increases vulnerability through male out-migration that increases the work to women (Chindarkar, 2012); cropping and livestock changes that affect gender division of labor (Lambrou and Paina, 2006); increased difficulty in accessing resources (fuelwood and water) (Tandon, 2007); and increased conflicts over natural resources (Omolo, 2011).

Women are generally, though not in every context, more vulnerable to the impacts of extreme events, such as floods and tropical cyclones (Neumayer and Plümper, 2007).

9.3.5.1.6. Knowledge and information

Lack of access to information and knowledge of rural people can also interact with all the above mentioned drivers to mediate vulnerability. Shared knowledge and lessons learned from previous climatic stresses provide vital entry points for social learning and enhanced adaptive capacity (Tschakert, 2007). But while some authors emphasize the need for local responses and indigenous knowledge to reduce vulnerability (Valdivia et al., 2010), and call for an integration of local knowledge into climate policies (Nyong et al., 2007; Brugger and Crimmins, 2012), Bellon et al. (2011) state that local knowledge is too local, and in some contexts gathering information from further away is important.

Access to information alone is not a guarantee of success. Coles and Scott (2009) found that in Arizona, despite ample access to weather forecasting, ranchers did not rely on such information, implying that changes are required to make more attractive information to users, as well as to understand prevailing local cultures and norms.

It is also important how knowledge is produced, managed, and disseminated within the formal institutional structure to address vulnerability issues. A local case study in Sweden shows that limited cooperation between local sector organizations, lack of local coordination, and an absence of methods and traditions to build institutional knowledge present barriers to manage vulnerability (Glaas et al., 2010). In Benin, as elsewhere in Africa, there is a lack of coordination between climate policies and the policies and practices that govern agricultural research and extension, while good practice at project level has been insufficiently harnessed to foster collective learning of farmers and other agricultural stakeholders, and thus adaptation to climate change (Moumouni and Idrissou, 2013a,b). For institutional learning, knowledge transfer, and more reliable assessments of local vulnerabilities, local institutional structure must be flexible, establishing communication mechanisms among public authorities, other knowledge producers, and civil society (Glaas et al., 2010).

9.3.5.2. Outcomes

The outcome of vulnerability is the result of, and interaction of, the driving forces that determine vulnerability in a given sector, social group, and so forth. This section analyzes how different drivers may affect specific vulnerable groups in rural areas, particularly pastoralists, mountain farmers, and artisanal fisherfolk. Box 9-2 takes a specific economic sector important in rural areas and demonstrates the interplay of vulnerability and exposure.

Box 9-2 | Tourism and Rural Areas

The three major market segments of tourism most liable to be affected by climate change are rural-based, namely, coastal tourism, nature-based tourism, and winter sports tourism (Scott et al., 2012). Tourism is a significant rural land use in many parts of the world, yet compared to other economic sectors in rural areas, the impacts of climate change are typically under-researched. In the Caribbean, for example, tourism has overtaken agriculture in terms of economic importance, with several regional states (including the Bahamas, the Cayman Islands, and St Lucia) receiving more than 60% of their GDP from this industry (Meyer, 2006). Coastal environments elsewhere in the world are also characterized by dependence on rural tourism, and are known to be vulnerable to cyclones and sea level rise (Payet, 2007; Klint et al., 2012a).

Terrestrial natural resource-based tourism is also a significant foreign exchange earner in many countries. In sub-Saharan Africa, between 25 and 40% of mammal species in national parks are *likely* to become endangered by 2080, assuming no species migration (and 10 to 20% with the opportunity for migration) (Thuiller et al., 2006). There are also many rural environments viewed as "iconic" or having cultural significance that are vulnerable to climate change. In South Africa, for example, the Cape Floral (fynbos) ecosystem has a high level of species endemism which will be vulnerable to the projected increase in dry conditions (Midgley et al., 2002; Boko et al., 2007). The projected increase in climate change-related hazards, such as glacial lake outbursts, landslides, debris flows, and floods, may affect trekking in the Nepali Himalayas (Nyaupane and Chhetri, 2009).

The development of tourism has, in many cases, increased levels of exposure to climate change impacts. In the Caribbean, for example, tourism has led to considerable coastal development in the region (Potter, 2000), which may exacerbate vulnerability to sea level rise. In many cases, the carbon emissions resulting from participating in rural tourism threaten the very survival of the areas being visited. This is often the case for very remote locations, for example, polar bear tourism in Canada (Dawson et al., 2010), and dive tourism in Vanuatu (Klint et al., 2012b). Although on aggregate resource consumption of tourists and locals has been shown to be similar in developed county contexts (e.g., in Italy; Patterson et al., 2007); in many developing countries resource use by tourists is much higher than that of locals (e.g., in Nepal; Nepal, 2008).

Despite the potential impacts of climate change on rural tourism, there is *low evidence* of significant concern, which impedes adaptive responses. Surveys in both the upper Norrland area of northern Sweden and New Zealand showed that climate change is not perceived to pose a major threat in the short term, relative to other business risks perceived by small business owners and tourism operators (Hall, 2006; Brouder and Landmark, 2011).

That said, there is evidence that, with planned adaptation, tourism can flourish in rural areas under climate change. In the Costa Brava region of Spain, for example, although the increasing temperatures and reduced water availability are projected to negatively impact tourism in the current high seasons, there is scope to shift to the current shoulder seasons, namely April, May, September, and October (Ribas et al., 2010). Recognition of the opportunities for adaptation has also necessitated reassessment of the extent of the potential impacts of climate change on the tourism industry in rural areas. With the availability of snowmaking as a (costly and uncertain) adaptation in the eastern North American ski industry, only 4 out of 14 ski areas are at risk before 2029, but 10 out of 14 in the period 2070–2099 (Scott et al., 2006).

9.3.5.2.1. Pastoralists

Pastoralists have developed successful strategies for responding to climate variability, especially "strategic mobility" in pursuit of high-quality grazing (Krätli et al., 2013), in combination with shorter-term coping strategies (Morton, 2006), for example, in sub-Saharan Africa (Davies and Bennett, 2007; Kristjanson et al., 2010) or Inner Mongolia (Wang and Zhang, 2012). However, mobility, a key component for community resilience, is declining , increasing the vulnerability of people in arid and semiarid regions (Lioubimtseva and Henebry, 2009; Fraser et al., 2011). The lack of other alternatives in certain marginal areas where animals are the only secure assets can lead to overstocking and overgrazing, and thus to increased vulnerability of pastoralism (Cooper et al., 2008).

This is "induced vulnerability" (Krätli et al., 2013), arising from a range of social, economic, environmental, and political pressures external to pastoralism that bring about encroachment on rangelands; inappropriate land policy; undermining of pastoral culture and values; and economic policies promoting uniformity and competition over diversity and complementarity. Other authors list as constituents of increased vulnerability: population growth; increased conflict over natural resources; changed market conditions and access to services under liberalization; concentration of political power in national centers; and perceptions that pastoralists are backward (Smucker and Wisner, 2008; Dougill et al., 2010; Dong et al., 2011; Rivera-Ferre and López-i-Gelats, 2012). These in turn can be seen as results of what Reynolds et al. (2007) conceptualize as two key features of dryland populations: remoteness, and distance from the centers and priorities of decision makers or "distant voice." However, Dong et al. (2011) and Sietz et al. (2011) stress the geographic differentiation of pastoral systems (and more broadly of dryland systems).

9.3.5.2.2. Mountain farmers

Mountain ecosystems have been identified as extremely vulnerable to climate change (Fischlin et al., 2007), and thus populations have a high exposure to climate change. A detailed understanding of climate change impacts in mountain areas is difficult because of physical inaccessibility and scarcity of resources for research in mountain states and regions (Singh et al., 2011), as well as more generic uncertainties relating to climate projection.

Mountain dwellers, as pastoralists in drylands, are adapted to live in steep and harsh and variable conditions, and thus have a variety of strategies to adapt and foster resilience to changing climatic conditions. However, to develop their strategies they need to overcome other drivers that can affect their vulnerability in different contexts. For instance, in most developed countries, mountains are becoming depopulated (Gehrig-Fasel et al., 2007; Gellrich et al., 2007; López-i-Gelats, 2013) given the extreme climatic conditions and their remoteness and subsequent isolation, while in developing countries (e.g., tropical mountain areas) there is a trend toward increasing population (Huber et al., 2005; Lama and Devkota, 2009). The impacts of the projected warming on mountain farming, as well as their adaptation strategies, differ spatially because the socioeconomic role of mountains varies significantly between industrialized and industrializing or non-industrialized countries (Nogués-Bravo et al., 2007). Mountain grasslands in developed countries are usually managed via a sub-exploitation model that involves the intensive use of the most productive areas and the abandonment of those regions where production is economically less viable (López-i-Gelats et al., 2011). In contrast, mountain grasslands in developing countries remain centers of fodder and livestock production. Thus, two general trends are identified in world mountain grasslands: while temperate mountain grasslands tend to suffer from conversion to agriculture, and land abandonment where livestock raising is less feasible (Gellrich et al., 2008), in tropical mountain grasslands the main cause of degradation is overgrazing, linked to processes of demographic growth. Land privatization, loss of grazing rights, or changes in land use (e.g., development of infrastructure) also affect mountain farmers both in developed and developing countries (Tyler et al., 2007; Xu et al., 2008).

9.3.5.2.3. Artisanal fisherfolk

Small coastal and riparian rural communities face several drivers that increase their vulnerability, which remain largely ignored by mainstream fisheries policy analysts; for example, the potential impact of demographic, health, and disease trends, or of wider development policy trends (Hall, 2011); pressure from other resources (e.g., water, agriculture, coastal defense); unbalanced property rights; and lack of adequate health systems, potable water, or sewage and drainage (Badjeck et al., 2010). The most important drivers affecting small-scale fisheries can be grouped into international trade and globalization of markets; technology; climate and environment; health and disease; demography; and development patterns and aquaculture. For instance, freshwater fisheries are threatened by increasing irrigation, while vulnerability of coastal fisheries increases with mangrove loss to aquaculture facilities in response to growing markets for prawns (Hall, 2011). Another difficulty faced by fisheries-based livelihoods is the neglect of governments and researchers, which is more focused on industrial fishing than artisanal fishing (Mills et al., 2011).

9.4. Adaptation and Managing Risks

9.4.1. Framing Adaptation

AR4 stated with *very high confidence* that adaptation to climate change was already taking place, but on a limited basis, and more so in developed than developing countries. Since then, the documentation of adaptation in developing countries has grown (*high confidence*). Adaptation is progressive, and is distinguished from coping as it reduces vulnerability in the case of re-exposure to the same hazard (Vincent et al., 2013): it can therefore be identified even without *high confidence* that a local hazard or climate trend is attributable to global climate change—indeed many cases of adaptation are driven primarily by other stressors, but have the result of aiding adaptation to climate change (Berrang-Ford et al., 2011).

Many adaptations do build on examples of responses to past variability in resource availability, and it has been suggested that the ability to cope with current climate variability is a prerequisite for adapting to future change (Cooper et al., 2008). At the same time, however, it cannot be assumed that past response strategies will be sufficient to deal with the range of projected climate change. In some cases, existing coping strategies may increase vulnerability to future climate change, by prioritizing short-term resource availability (Adepetu and Berthe, 2007; O'Brien et al., 2007). In Malawi, for example, forest resources are used for coping (gathering wild food and firewood to sell), but this process reduces the natural resource base and increases vulnerability to future flooding through reduced land cover and increased overland flow (Fisher et al., 2010). In developing countries, there is *high confidence* that adaptation could be linked to other development initiatives aiming for poverty reduction or improvement of rural areas (Eriksen and O'Brien, 2007; Hassan, 2010; Nielsen et al., 2012; see also Section 13.4). For more information on the integration of adaptation and development in climate-resilient development pathways, see Chapter 20. In Ethiopia, for example, "low regrets" measures to respond to current variability are important to shift the trajectory from disaster-focused to longer-term vulnerability reduction (Conway and Schipper, 2011).

9.4.2. Decision Making for Adaptation

Decision making for adaptation takes place at a variety of levels, and can be public or private. International mechanisms variously support adaptation decision making at all levels (see Sections 14.4, 15.2). At the national and local levels, law and policies can enable planned adaptation (Stuart-Hill and Schulze, 2010). A longer history of evidence for public policies to support adaptation exists for developed countries, although increasingly developing countries are also introducing such policies (for more information, see Section 15.2, Box 25-2 on Australia's water policy and management, and Section 26.9.1 on federal adaptation policies in the USA and Canada). At local levels, some progress toward adaptation planning has been observed, particularly in developed countries. In Australia, for example, western Australia, South Australia, and Victoria have mandatory State planning benchmarks for 2100 (see Box 25-1) and, in the Great Plains of the USA, some jurisdictions have developed plans on either climate adaptation or climate mitigation, although so far fewer than 20% have done so (Romsdahl et al., 2013). At the local level, many adaptations are examples of private decisions for adaptation, undertaken by NGOs (primarily in developing countries, often in the form of community-based adaptation), and companies and individuals. Public and private decision making for adaptation is not always mutually exclusive: one example of where policy can support private adaptation is in the provision of index-based insurance schemes (Linnerooth-Bayer and Mechler, 2007; Suarez and Linnerooth-Bayer, 2010), which have variously been trialed in India, Africa, and South America (Patt et al., 2009, 2010; for a case study on index-based weather insurance in Africa, see Box 22-1). However, national policies and laws are not always mutually supportive of private actions (Stringer et al., 2009).

There is now *high confidence* that public decision making for adaptation can be strengthened by understanding the decision making of rural people in context, and in particular considering examples of autonomous adaptation and the interplay between informal and formal institutions (Bryan et al., 2009; Eakin and Patt, 2011; Adhikari and Taylor, 2012; Naess, 2012). Adaptation can also build upon local and indigenous knowledge for responding to weather events and a changing climate as has been observed in Samoa (Lefale, 2010; see Chapter 29), the Solomon Islands (Rasmussen et al., 2009; see Chapter 29), Namibia (Newsham and Thomas, 2011), Canada (Nakashima et al., 2011; see Chapter 24), the Indo-Gangetic Plains (Rivera-Ferre et al., 2013b), and Australia (Green et al., 2010).

9.4.3. Practical Experiences of Adaptation in Rural Areas

In AR4, examples of adaptation in rural areas exhibited a bias toward developed countries (WGII AR4 Chapter 17), but since then practical examples of adaptation in rural areas have increased substantially in developing countries (*very high confidence*). These practical experiences of adaptation are found in agriculture, water, forestry and biodiversity, and fisheries.

9.4.3.1. Agriculture

Agricultural societies have a history of responding to the impacts of change in exogenous factors, including (but not limited to) weather and climate (Mertz et al., 2009a). They undertake a range of adjustment measures relating to their farming practices—for example, planting, harvesting, and watering/fertilizing existing crops; using different varieties; diversifying crops; and implementing management practices such as shading and conservation agriculture. Table 9-7 gives some examples; Box 9-3 describes adaptation initiatives in the beverage crop sector. More information on agricultural adaptation is available in Sections 23.8.2 (Europe), 24.4.3.5 (Asia), 25.7.2 (Australasia), 26.5.4 (North America), and 27.3.4.2 (Central and South America).

Conservation agriculture shows promising results and can be used as an adaptation (Speranza, 2013) and for sustainable intensification of production (Pretty et al., 2011), with significant yield productions observed in South Asia and southern Africa (Erenstein et al., 2012). See Box 22-2 for a case study on integrating trees into annual cropping systems. Water management for agriculture is also critical in rural areas under climate change, for example, the use of rainwater harvesting (Vohland and Barry, 2009; Kahinda et al., 2010; Rivera-Ferre et al., 2013b), and more efficient irrigation, particularly in rural drylands (Thomas, 2008).

Adaptations are also evident among small-scale livestock farmers (Kabubo-Mariara, 2008, 2009; Rivera-Ferre and López-i-Gelats, 2012), who use many different strategies, including changing herd size and composition, grazing and feeding patterns, or diversifying their livelihoods; also they may use new varieties of fodder crops suited to the changing conditions (Salema et al., 2010).

Diversified farms are more resilient than specialized ones (Seo, 2010); but rural societies also diversify their income sources beyond agriculture, which in many contexts allows them to reduce their risk exposure. Examples include the exploitation of gums and resins in Kenya (Gachathi and Eriksen, 2011).There may be some rural areas, however, where limits to agricultural adaptation are reached, and thus the only option that remains is to migrate or diversify away from farming (Mertz et al., 2011). According to Chapter 7, adaptation leads to lower reductions in food production with more effective adaptation (of around 15 to 20% compared with no adaptation), and adaptations are more successful at higher latitudes (for maize, wheat, and rice) than in tropical regions. Figure 7-8 shows the varying efficiency of different crop adaptation measures, with cultivar adjustment leading to the largest percentage difference from the baseline, compared with irrigation optimization and planting date adjustment (although this shows the largest variation).

9.4.3.2. Water

As well as being an important input to agriculture, adaptation in water resources through improved management is critical in rural areas, not only at basin level but also for human settlements (Mukheibir, 2008). The extent to which adaptation measures have been implemented to date varies: in a study from Europe, Africa, and Asia, European basins were most advanced (Krysanova et al., 2010). In the cases of transboundary basins additional barriers exist to adaptive management measures, particularly in Africa (Goulden et al., 2009), although examination of potential institutional designs has been undertaken

Table 9-7 | Examples of adaptations in the agricultural sector in different regions.

Agricultural adaptations	Examples	Where observed	Source
Modifying planting, harvesting, and fertilizing practices for crops	Maize and wheat crops	Central and South America (Bolivia, Argentina, Chile); South Africa (including North West, Limpopo, and KwaZulu-Natal provinces)	PNCC (2007), Thomas et al. (2007), Magrin et al. (2009), Meza and Silva (2009)
	Composting and coralling of livestock to collect waste	Africa (South Africa, including North West, Limpopo, and KwaZulu-Natal provinces; northern Burkina Faso; Sahelian region of Mali)	Adepetu and Berthe (2007), Thomas et al. (2007), Barbier et al. (2009), Bryan et al. (2009)
Changing amount or area of land under cultivation		South Africa	Bryan et al. (2009)
	Moving winter wheat northwards	China	Lin et al. (2005)
	Expansion of fields	Northern Burkina Faso	Barbier et al. (2009)
	Increase in the size of plots	Sahelian region of Mali	Adepetu and Berthe (2007)
Using different varieties (e.g., early maturing, drought-resistant)	Early maturing cultivars	South Brazil	Walter et al. (2010)
		North America	Coles and Scott (2009)
	Drought-tolerant cultivars	Asia	Thomas (2008), Zhao et al. (2010)
		South Africa and Ethiopia	Bryan et al. (2009)
		Ghana	Gyampoh et al. (2008)
		Northern Burkina Faso	Barbier et al. (2009)
		Sahelian region of Mali and Nigeria	Adepetu and Berthe (2007)
		North West, Limpopo, and KwaZulu-Natal provinces of South Africa	Thomas et al. (2007)
Diversifying crops and/or animal species	Crops	Peruvian Andes	Lin (2011)
		South America	Montenegro and Ragrab (2010)
		Northeastern Mexico	Eakin and Appendini (2008), Eakin and Bojorquez-Tapia (2008)
		Tasmania, Australia	Smart (2010)
		KwaZulu-Natal, South Africa	Thomas et al. (2007)
	Replacing cattle with hardier goats and camels	Kenya	Rivera-Ferre and López-i-Gelats (2012)
Commercialization of agriculture		Ghana	Gyampoh et al. (2008)
		Limpopo Province, South Africa	Thomas et al. (2007)
	Income generation from natural resources (e.g., fuelwood)	Limpopo River Basin, Botswana	Dube and Sekhela (2007)
Water control mechanisms (including irrigation and water allocation rights)	Improved rice harvests	Monsoonal Asia	Hatcho et al. (2010)
	Adaptation for quinoa	Bolivian Altiplano	Geerts and Raes (2009)
	Adaptation for tomatoes	Central Brazil	
	Adaptation for cotton	Northern Argentina	
	Adaptation for rice	Northeast China	Lin et al. (2005)
	Small water harvesting pits in improved yields and incomes due to improved soil moisture	Ethiopia	Bryan et al. (2009), Amede et al. (2011)
		Burkina Faso	Barbier et al. (2009), Hertsgaard (2011)
		South Africa	Bryan et al. (2009)
		Ghana	Gyampoh et al. (2008)
	Dry season vegetable production through irrigation to enable two crop cycles	Northern Burkina Faso	Barbier et al. (2009)
		Sahelian region of Mali and Nigeria	Adepetu and Berthe (2007)
		Limpopo Province, South Africa	Thomas et al. (2007)
Shading and wind breaks	For coffee	Brazil, Costa Rica, and Colombia	Camargo (2010)
		Ethiopia	Bryan et al. (2009)
Conservation agriculture (e.g., soil protection, agroforestry)		Honduras, Nicaragua, and Guatemala	Holt-Gimenez (2002)
		Burkina Faso	Barbier et al. (2009), Hertsgaard (2011)
		Ethiopia	Bryan et al. (2009)
		Sahelian region of Mali	Adepetu and Berthe (2007)

Continued next page →

Table 9-7 (continued)

Agricultural adaptations	Examples	Where observed	Source
Modifying grazing patterns for herds	Utilizing spatial variability in resources	Arctic	Bartsch et al. (2010)
		East Africa	Eriksen and Lind (2009)
		Southern Africa	O'Farrell et al. (2009)
		Northern Burkina Faso	Barbier et al. (2009)
		Sahelian region of Mali and Nigeria	Adepetu and Berthe (2007)
		North West, Limpopo, and KwaZulu-Natal provinces, South Africa	Thomas et al. (2007)
Providing supplemental feeding for herds/storage of animal feed		Arctic	Forbes and Kumpula (2009)
		South Africa	Bryan et al. (2009)
	Use of sorghum and hay residue for feeding livestock	Northern Burkina Faso	Barbier et al. (2009)
		Sahelian region of Mali and Nigeria	Adepetu and Berthe (2007)
	Cutting fodder for livestock	Limpopo Province, South Africa	Thomas et al. (2007)
Ensuring optimal herd size	Changing size of European reindeer herds to match pasture availability	Northern areas of Norway, Sweden, Finland, and Russia	Rees et al. (2008)
	Culling of livestock	Northern Nigeria	Adepetu and Berthe (2007)
	Selling of livestock	Northern Burkina Faso	Barbier et al. (2009)
		Sahelian region of Mali and Nigeria	Adepetu and Berthe (2007)
Developing new crop and livestock varieties	Biotechnology and breeding	Brazil and Argentina	Urcola et al. (2010), Marshall (2012)
		Northern Nigeria	Adepetu and Berthe (2007)

(Huntjens et al., 2012). In the Middle East and North Africa, while supply-side measures are advanced, little attention has been paid to the demand-side measures that will be critical in a changing climate (Sowers et al., 2011).

While the majority of focus on adaptation concerning water relates to its availability, many rural areas in both developed and developing countries are subject to riverine or coastal flooding. In the low-lying Netherlands protection measures have been employed, including increasing river runoff, increasing storage for water (Deltacommissie, 2008; Kabat et al., 2009), and small-scale containment of flood risks through increasing compartmentalization (Klijn et al., 2009). In the Mekong Delta in Vietnam, the government's "living with floods" program has encouraged rice farmers to shift to aquaculture, while the planned relocation of 20,000 "landless and poor households" has altered social networks and livelihoods (De Sherbinin et al., 2011). See Table 9-8 for further examples.

More information on adaptation in the water sector is available in Sections 24.4.1.5 and 24.4.2.5 (Asia), 26.3.3 (North America), and 27.3.1.2 and 27.3.2.2 (Central and South America).

9.4.3.3. Forestry and Biodiversity

Effective management is also essential for adaptation of forests and biodiversity to climate change, particularly involving (where appropriate) communities (Porter-Bolland et al., 2012). Forest resources have been shown to play a role in enabling livelihood adaptation during extreme events in Zambia, Mali, and Tanzania, although it should take place

Table 9-8 | Examples of adaptations in the water sector observed in different regions.

Type	Example	Where it has been observed and source
Supply-side mechanisms	Dams	Proposed in the Volta River in Ghana (van de Giesen et al., 2010)
	Reservoirs	Asia (Tyler and Fajber, 2009), particularly in areas where water stress is an issue of distribution rather than absolute shortage (Biemans et al., 2011; Rivera-Ferre et al. 2013)
	Groundwater pumping	Arid and semi-arid South America (Döll, 2009; Kundzewicz and Döll, 2009; Zagonari, 2010; Burte et al., 2011)
	Groundwater recharge	Potential identified in India (Sukhija, 2008)
	Irrigation (often using water-saving technology)	Asia (Ngoundo et al., 2007; Tischbein et al., 2011)
	Fog interception practices	South America (Holder, 2006; Klemm et al., 2012)
	Water capture	Bolivia (PNCC, 2007)
Demand-side mechanisms	Improved management, e.g., through efficiency	Asia (Kranz et al., 2010), South America (Geerts et al., 2010; Montenegro and Ragab, 2010; Van Oel et al., 2010; Bell et al., 2011); Argentine Pampas (Quiroga and Gaggioli, 2010)
	Policies	Murray-Darling Basin Authority (MDBA) established to address over-allocation of water resources (Connell and Grafton, 2011; MDBA, 2011). See also Box 25-3 on Australia's water policies.
	Reviewing allocation rights	Indogangetic Plains (Rivera-Ferre et al., 2013b); Australia's MDBA reviewed the "exceptional circumstances" concept in drought policy (Productivity Commission, 2009)

Box 9-3 | Adaptation Initiatives in the Beverage Crop Sector

One of the leading initiatives to prepare small-holder producers of beverage crops for adaptation to climate change is the AdapCC project, which worked with coffee and tea producers in Latin America and East Africa (Schepp, 2010). This process used risk and opportunity analysis and participatory capacity building (CafeDirect/GTZ, 2010) to help farmers identify changes in management practices to both mitigate their contribution to climate change and adapt to the changes in climate they perceived to be occurring. In general the actions for adaptation were a reinforcement of principles of sustainable production, such as using tree shade. Facilitating processes of adaptation in the context of strong variability in vulnerability between different communities in the same region and even families within the same community (Baca Gómez, 2010) will be a challenge, but supports the need for participatory community adaptation processes that would enable families to implement strategies appropriate to their own circumstances and capacity.

Policy recommendations to support adaptation in these sectors (Schroth et al., 2009; Laderach et al., 2010; Schepp, 2010; Eakin et al., 2011) have prioritized the following interventions to support adaptation:

- Community-based analysis of climate risks and opportunities as a basis for community adaptation strategies
- Improved recording and access to climate information including medium- and long-term predictions
- Sustainable production techniques including soil and water conservation, shaded production systems, diversification of production systems
- Development of new varieties with broader adaptability to climate variation, higher temperatures, and increased drought tolerance
- Financial support to invest in adaptation and reduce risks through climate insurance
- Organization of small producers to improve access to knowledge and financial support, and to coordinate implementation
- Environmental service payments and access to carbon markets to support sustainable practices
- Development of value chain strategies across all actors to support adaptation and increase resilience across the sectors.

There are possibilities for synergy between adaptation and mitigation. The sustainability standards Rainforest Alliance and Common Code for the Coffee Community are piloting climate-friendly standards for producers that aim to reduce the greenhouse gas emissions from agricultural practices and to increase sequestration of carbon in soils and trees, but also to prepare producers for adapting to climate change (Linne, 2011; SAN, 2011). The latter consists of improved understanding of climate impacts and promoting sustainable production practices to increase resilience in the production systems.

within a managed context to ensure sustainability (Robledo et al., 2011). As with water resources, forests can adapt through management of forest fires, silvicultural practices, and the conservation of forest genetic resources. Ecological restoration, where required, is another effective adaptation measure that enhances biodiversity and environmental services (Benayas et al., 2009), increases the potential for carbon sequestration, and promotes economic livelihoods in rural areas (Chazdon, 2008), as seen in examples of the Brazilian Atlantic Forest (Calmon et al., 2011; Rodrigues et al., 2011). Direct species management is important (Mawdsley et al., 2009). In terms of managing protected areas, to maintain appropriate habitats a network approach may be effective (Hole et al., 2011).

As the climate changes, part of adaptive management may entail modification of existing biodiversity management practices. Manipulating vegetation composition and stand structure, for example, has been proposed as an adaptation option to wildfires in Canada (Girardin et al., 2013; Terrier et al., 2013); for more information on wildfires see Box 26-2. In Central and South America, protected areas of restricted use reduced fire substantially, but multi-use protected areas are even more effective; and in indigenous reserves the incidence of forest fire was reduced by 16% as compared to non-protected areas (Nelson and Chomitz, 2011).

Reflecting the growing evidence for community-based management and wise use, an emerging mechanism for ecosystem-based adaptation includes payment for ecosystem services (PES) (Montagnini and Finney, 2011). The PES literature is more developed for carbon payments, CDM and REDD+, but some research suggests potential for adaptation as well (see Section 13.3.1.2 for an assessment of the relationship between REDD+ and poverty alleviation). Particularly developed in Central and South America (see Table 27-7 for examples of PES schemes), communities can be paid for collecting scientific data to contribute to research and monitoring protocols (Luzar et al., 2011), or for actively managing natural resources, which may improve adaptive capacity in the longer term, bearing in mind with reforestation there is a time delay before payments are received (Locatelli et al., 2008). More indirectly, there are opportunities for PES to contribute to adaptation indirectly through natural adaptation co-benefits (e.g., water regulation and soil protection for reduced climate impacts in watersheds) (Pramova et al., 2012) and through the creation of institutional structures that may support adaptive capacity (Wertz-Kanounnikof et al., 2012). For further case studies on ecosystem-based adaptation, see Figure 22-8 (Africa), Box CC-EA, and Section 14.3.2; and for a diagrammatic representation see Figure CC-EA-1. More information on adaptation for forestry and biodiversity is available in Sections 23.8.2 and 23.8.4 (Europe), 24.5.1 (Asia), and 25.7.1.2 (Australasia).

9.4.3.4. Fisheries

Adaptation in marine ecosystems is also of relevance to rural areas. As with terrestrial natural resources, evidence from the marine resources sphere shows that a transformative approach to fisheries co-management, introducing ecosystem rights, and participation principles is essential for adaptation (Andrew and Evans, 2011; Charles, 2011). Such an approach, involving local fishermen and allowing limited extraction of resources, favors a balance between resource conservation and livelihoods, for example, in Brazil (Francini-Filho and Moura, 2008), and the improvement of livelihoods, as well as the cultural survival of traditional populations (Moura et al., 2009; Hastings, 2011) (see also Section 30.6.2.1). Selective use of fishing gear is a recommended management measure, based on 15 global sites, to ensure sustainable harvesting of remaining fish stocks (Cinner et al., 2009). According to Section 6.4.1.1, appropriate management will have a greater impact on biological and economic conditions than climate change. Table 30-2 outlines potential adaptation options and supporting policies for fisheries and aquaculture in the Pacific Islands considering a variety of time scales. Section 7.5 gives additional examples on adaptation for aquaculture.

9.4.4. Limits and Constraints to Rural Adaptation

The Fourth Assessment Report stated with *very high confidence* that there are substantial limits and barriers to adaptation (Adger et al., 2007). Limits are typically defined (Dow et al., 2013) as hard, that is, they will not change over time, and are particularly applicable to biophysical systems (where, e.g., there are critical thresholds to species and ecosystem tolerances of climate parameters and regimes). Constraints, on the other hand, are typically soft, and are more relevant to social systems, where changes in factors such as financial and physical resources, technology and infrastructure, knowledge and information, and human resources may change over time. For further information, see Figure 16-1 and Sections 16.3.2 and 16.4.1. Here we focus on the soft constraints in social systems that act as barriers to implementation of practical adaptation options in rural areas.

As with risks and vulnerabilities, the literature emphasizes constraints to adaptation in rural areas in developing regions, although adaptation bottlenecks exist also in developed countries (where there has been an increase in awareness and planning for adaptation, but that has not necessarily translated into implementation; see Chapter 14). Constraints to adaptation in developed regions have been observed in North America (Section 26.8.4.2) and Australasia (Section 25.4.2; Boxes 25-1, 25-2, 25-9). Another key bottleneck comes from the fact that the need for adaptation to climate change is not the only pressing issue in rural areas in developed countries (Kiem and Austin, 2013).

There is *very high confidence* that lack of financial resources (in the form of credit) and physical resources (such as water and land) are major factors inhibiting adaptation for farmers in Africa and Asia (e.g., Hassan and Nhemachena, 2008; Bryan et al., 2009; Deressa et al., 2009; Ringler, 2010). A multinomial logit analysis of climate adaptation responses suggested that access to water, credit, extension services, and off-farm income and employment opportunities, tenure security, farmers' asset base, and farming experience are key to enhancing farmers' adaptive capacity (Gbetibouo et al., 2010).

Rural households' lack of access to technologies and infrastructure (e.g., markets) is also a major barrier to adaptation for certain production systems (*medium evidence*, *high agreement*). According to a study of adoption of improved, high yield maize in Zambia, production and price risks could render input use unprofitable and prevent rural households from benefiting from technological change crucial for adaptation (Langyintuo and Mungoma, 2008). The severe 1997 drought in the Central Plateau of Burkina Faso highlighted that households with a larger resources base took advantage of distress sales and high prices of agricultural commodities (Roncoli et al., 2001). A nationally representative rural household survey in Mozambique from 2005 shows that, overall, using an improved technology (improved maize seeds, improved granaries, tractor mechanization, and animal traction) did not have a

Frequently Asked Questions

FAQ 9.3 | What will be the major ways in which rural people adapt to climate change?

Rural people will in some cases adapt to climate change using their own knowledge, resources, and networks. In other cases governments and other outside actors will have to assist rural people, or plan and execute adaptation on a scale that individual rural households and communities cannot. Examples of rural adaptations will include modifying farming and fishing practices; introducing new species, varieties, and production techniques; managing water in different ways; diversifying livelihoods; modifying infrastructure; and using or establishing risk-sharing mechanisms, both formal and informal. Adaptation will also include changes in institutional and governance structures for rural areas.

Box 9-4 | Factors Influencing Uptake and Utility of Climate Forecasts in Rural Africa

The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) identified the use of forecasts as a risk management measure (IPCC, 2012). So far the uptake of weather and climate information has been suboptimal (Vogel and O'Brien, 2006). In Africa annual climate information (e.g., seasonal forecasts) is more used than climate change scenarios for agricultural development (Ziervogel and Zermoglio, 2009), although attempts to use longer-term climate projections for crop forecasting and livestock farming have been examined (Boone et al., 2004; Challinor, 2009). The potential for improved prediction and effective timely dissemination of such information has been noted in different sectors, including water managers (Ziervogel et al., 2010a) and disaster planners (Tall et al., 2012), as well as farmers (both arable and pastoral) (Klopper et al., 2006; Archer et al., 2007; Bryan et al., 2009).

Extensive research has taken place to assess factors influencing uptake and utility of climate forecasts, including mapping of dissemination through stakeholder networks (Ziervogel and Downing, 2004), and user needs (Ziervogel, 2004). Such studies have shown that various factors affect dissemination and use, including stakeholder involvement in the process (usually higher when participatory processes had taken place) (Roncoli et al., 2009; Peterson et al., 2010); effects of user wealth, risk aversion, and presentational parameters, such as the position of forecast parameter categories, and the size of probability categories (Millner and Washington, 2011); and the legitimacy, salience, access, understanding, and capacity to respond (Hansen et al., 2011). Gender differences have been observed in preferred dissemination channels (Archer, 2003; Naab and Korenteng, 2012).

There are promising signs for the integration of scientific-based seasonal forecasts with indigenous knowledge systems (Speranza et al., 2010; Ziervogel et al., 2010b). Ensuring improved validity and utility of seasonal forecasts will require collaboration of researchers, data providers, policy developers, and extension workers (Coe and Stern, 2011), as well as with end users. Additional opportunities to benefit rural communities come from expanding the use of seasonal forecast information for coordinating input and credit supply, food crisis management, trade, and agricultural insurance (Hansen et al., 2011). For more information on climate information and services, and the history, politics, and practice of this area, see Section 2.4.1.

statistically significant impact on household income. However when distinguishing between households using improved technologies, especially improved maize seeds and tractors, and those who do not, households that had better market access had significantly higher income (Cunguara and Darnhofer, 2011). A multinomial choice model fitted to data from a cross-sectional survey of more than 8000 farms from 11 African countries showed that better access to markets, extension and credit services, technology, and farm assets (labor, land, and capital) are critical for helping African farmers adapt to climate change. Hence education, markets, credit, and information about adaptation to climate change, including technological and institutional methods, are important (Hassan and Nhemachena, 2008).

Although access to credit, water, technologies, and markets are barriers, more fundamental is access to knowledge and information (*very high confidence*). Because adaptation strategies involve dealing with uncertainty, whether stakeholders have access to information for decision making and how they perceive and utilize this information affects their adaptation choices (Dockerty et al., 2006; Sheate et al., 2008; Patt and Schröter, 2008; Bryan et al., 2009; Deressa et al., 2009; Ringer, 2010). Relevant information includes that on agricultural technologies that can be used in adaptation, but in developing countries agricultural research and extension systems are not integrated with climate planning to deliver this, as discussed by Moumouni and Idrissou (2013a) for Benin. There is now an important literature on dissemination of short-term or seasonal weather forecasts to farmers in developing countries (see Box 9-4).

Access to information is affected by human resources, or social characteristics (*medium evidence*, *high agreement*). These include culture, gender, age, governance, and institutions (Deressa et al., 2009; Goulden et al., 2009; Nielsen and Reenberg, 2010; Jones and Boyd, 2011). A growing body of literature investigates the socio-cognitive, psychological, and cultural barriers to adaptation. Section 2.2.1.2 explains how culture and psychology affect decision making; Section 16.2 also discusses how the framing of adaptation depends on perception of risk and values. For planned adaptation to be successful, or autonomous adaptation to occur, actors need to be convinced of the magnitude of risks of climate change (Patt and Schröter, 2008).

9.5. Key Conclusions and Research Gaps

9.5.1. Key Conclusions

This chapter has assessed impacts of climate change, vulnerability to climate change, and prospects for adaptation to climate change in the rural areas of the world. Rural areas are distinctive and important in the context of climate change because:

- They account for nearly half of the world's population, even with rapid urbanization.
- They account for well over half of the world's poor and extremely poor people.
- Economic activity and livelihoods in rural areas are closely linked to natural resources and thus particularly sensitive to climate variability and climate change.
- Conversely, it is in rural areas that long-established adaptations to climate variability exist and can form a basis under certain conditions for adaptations to climate change.

Rural areas are hard to define—there is no internationally valid definition, and definitions that do exist depend on definitions of the urban (see Table 9-1). They are also extremely diverse, existing in nearly every country of the world, across low-, middle-, and high-income countries, although 90% of the world's rural population lives in low- and middle-income countries, which receive particular attention in this chapter. Rural areas are undergoing important and rapid changes in terms of their demography, economic profile, and governance (see Table 9-3)—some specific to developing countries, some to high-income countries, and some generic. Many of these changes are in the direction of economic and livelihood diversification away from agriculture and natural resources. Others are in the direction of increased rural-urban interdependencies and less well-defined boundaries between the rural and the urban.

Many of the non-climate factors characterizing rural areas and populations within them, especially in low- and middle-income countries, are cited as factors increasing vulnerability to climate change. There is *high agreement* on the importance for resilience of access to land and natural resources, flexible local institutions, and knowledge and information, and the association of gender inequalities with vulnerability. There are *low levels of agreement* on some of the key factors associated with vulnerability or resilience in rural areas, including rainfed as opposed to irrigated agriculture, small-scale and family-managed farms, and integration into world markets. Specific livelihood niches such as pastoralism and artisanal fisheries are vulnerable and at high risk of adverse impacts (*high confidence*), partly due to neglect, misunderstanding, or inappropriate policy toward them on the part of governments (Section 9.3.5).

Against this background, discussion of impacts of climate change will be complex. The impacts of climate change on patterns of settlement, livelihoods, and incomes in rural areas will be the result of multi-step causal chains of impact, starting either with increased frequency of extreme events or with more gradual manifestations of climate change, and working through impacts on agriculture, ecosystems, or infrastructure. This increases the uncertainty associated with any particular projected impact. Biophysical impacts on food production are discussed in Chapter 7: this is supplemented here by an assessment of impacts on the production of non-food crops on which many millions of rural people depend, illustrated in particular by coffee, tea, and cocoa (Box 9-1). Literature on the downstream impacts on incomes and livelihoods of changes in agricultural production (including livestock and fisheries) is also assessed.

Despite methodological problems in attribution, around the difficulties of attributing extreme events to climate change, the status of local knowledge, and the action of non-climate shocks and trends, evidence for observed impacts, both of extreme events and other categories, is increasing. Impacts on income and livelihoods can be inferred from biophysical impacts, but with *low confidence*. There is *high confidence* in geographically specific impacts such as glacier melt in the Andes (Section 9.3.2).

Major impacts of climate change in rural areas will be felt through impacts on agricultural production and therefore through agricultural incomes. In some regions shifts in agricultural production, of food and non-food crops, are *likely* to take place, not only as a result of changes in temperature and rainfall, but also through changes in availability of irrigation water, which are not necessarily factored into crop yield projections based on crop models (Section 9.3.3.1). There are also *likely* to be impacts on rural infrastructure both in developing and developed countries (Section 9.3.3.2).

The interconnections between rural and urban areas will be affected in complex ways. Climate change will impact international trade volumes in both volume and value terms (*limited evidence*, *medium agreement*). Options exist for adaptations within international agricultural trade (*medium confidence*) to reduce market volatility and manage food supply shortages caused by climate change. Migration patterns will be driven by multiple factors of which climate change is only one (*high confidence*) and establishment of a relation between climate change and intra-rural and rural-to-urban migration, observed or projected, remains a major challenge (Section 9.3.3.3).

Climate policies, such as increasing energy supply from renewable resources, encouraging cultivation of biofuels, or payments under REDD, will have significant secondary impacts, both positive (increasing employment opportunities) and negative (landscape changes, increasing conflicts for scarce resources), in some rural areas (*medium confidence*). These secondary impacts, and trade-offs between mitigation and adaptation in rural areas, have implications for governance, including the need to promote participation of rural stakeholders (Section 9.3.3.4).

Most studies on valuation highlight that climate change impacts will be significant especially for the developing regions, due to their economic dependence on agriculture and natural resources, low adaptive capacities, and geographical locations (*very high confidence*). In rural areas especially, valuation of climate impacts needs to draw upon both monetary and non-monetary indicators.The valuation of non-marketed ecosystem services and the limitations of economic valuation models that aggregate across multiple contexts pose challenges for valuing impacts in rural areas and require interdisciplinarity and innovative approaches (Section 9.3.4).

There is a growing body of literature on successful adaptation in rural areas and constraints upon it, including both documentation of practical experience and discussion of preconditions (Section 9.3.4). In developing countries adaptation can be linked to other development initiatives aiming for poverty reduction or improvement of rural areas, and "low regrets" measures to respond to current variability can shift the trajectory from disaster-focused to longer-term vulnerability reduction. Prevailing constraints, such as low levels of educational attainment, environmental degradation, gender inequalities, and isolation from decision making, create additional vulnerabilities which undermine rural societies' ability to cope with climate risks (*high confidence*). The supply of information and opportunities for learning will be a key issue.

9.5.2. Research Gaps

There is a major continuing need for research on climate change in rural areas, which takes in their nature as areas with shifting combinations of human activity, in which agriculture (food crops, non-food crops, and livestock) is important but not necessarily predominant. Such research will need to be developed, and extended to rural areas and diverse categories of rural people throughout the world.

Integrated research is needed on changes in land use and trade-offs between land uses under climate change, including non-agricultural land uses such as conservation and tourism. It should examine the trade-offs and synergies between adaptation and mitigation in rural areas, the impact of climate policies on rural livelihoods, and the appropriate structures for governance of natural resources at a landscape level for both developed and developing countries.

Research is required on the valuation and costing of climate change impacts, which takes note of the complexity and specificity of rural areas, with special emphasis on non-marketed ecosystem services and specific populations that have not as yet been studied.

More research is needed on vulnerability, to identify the most vulnerable areas, populations, and social categories, but it should include research on methodological questions such as conceptualizations of vulnerability, assessment tools, spatial scales for analysis, and the relations between short-term support for adaptation, policy contexts and development trajectories, and long-term resilience or vulnerability.

A relevant area will be that of improving understanding of rural-urban linkages, their evolution, and their management under climate change, including the respective roles of climate and other factors in rural-urban migration.

Research is needed on practical adaptation options, not only for agriculture but also for non-agricultural livelihoods. Adaptation research must also look at adaptations to institutions, to better enable them to address lack of access to credit, markets, information, risk-sharing tools, and property rights. Research must be open to participatory and action-research approaches that build on both local and scientific knowledge, and foster learning for adaptation and resilience among rural people.

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10 Key Economic Sectors and Services

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10

Executive Summary

This chapter assesses the implications of climate change on economic activity in key economic sectors and services, on economic welfare, and on economic development.

For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers (*medium evidence*, *high agreement*). Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change. {10.10}

Climate change will reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*robust evidence*, *high agreement*); the balance of the two depends on the geographic, socioeconomic, and technological conditions. Increasing income will allow people to regulate indoor temperatures to a comfort level that leads to fast growing energy demand for air conditioning even in the absence of climate change in warm regions with low income levels at present. Energy demand will be influenced by changes in demographics (upward by increasing population and decreasing average household size), lifestyles (upward by larger floor area of dwellings), the design and heat insulation properties of the housing stock, the energy efficiency of heating/cooling devices, and the abundance and energy efficiency of other electric household appliances. The relative importance of these drivers varies across regions and will change over time. {10.2}

Climate change will affect different energy sources and technologies differently, depending on the resources (water flow, wind, insolation), the technological processes (cooling), or the locations (coastal regions, floodplains) involved (*robust evidence*, *high agreement*). Gradual changes in various climate attributes (temperature, precipitation, windiness, cloudiness, etc.) and possible changes in the frequency and intensity of extreme weather events will progressively affect operation over time. Climate-induced changes in the availability and temperature of water for cooling are the main concern for thermal and nuclear power plants. Several options are available to cope with reduced water availability but at higher cost; however, decreased efficiency of thermal conversion remains a primary concern. Similarly, already available or newly developed technological solutions allow firms to reduce the vulnerability of new structures and enhance the climate suitability of existing energy installations. {10.2}

Climate change may influence the integrity and reliability of pipelines and electricity grids (*medium evidence*, *medium agreement*). Pipelines and electric transmission lines have been designed and operated for more than a century in diverse and often extreme climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. Owing to the private nature and high economic value to the energy sector, they have been designed to higher tolerance levels than most transportation infrastructure. Climate change may require changes in design standards for the construction and operation of pipelines and power transmission and distribution lines. Adopting existing technology from other geographical and climatic conditions may reduce the cost of adapting new infrastructure as well as the cost of retrofitting existing pipelines and grids to the changing climate, sea level, and weather conditions, which is likely to become more intense over time. {10.2}

Climate change will have impacts, positive and negative and varying in scale and intensity, on water supply infrastructure and water demand (*robust evidence*, *high agreement*), but the economic implications are not well understood. Economic impacts include flooding, scarcity, and cross-sectoral competition. Flooding can have major economic costs, both in term of impacts (capital destruction, disruption) and adaptation (construction, defensive investment). Water scarcity and competition for water—driven by institutional, economic, or social factors—may mean that water is not available in sufficient quantity or quality for some uses or locations. {10.3}

Climate change may negatively affect transport infrastructure (*limited evidence*, *high agreement*). Transport infrastructure malfunctions if the weather is outside the design range, which would happen more frequently as the climate continues to change. All infrastructure is vulnerable to freeze-thaw cycles. Paved roads are particularly vulnerable to temperature extremes, and unpaved roads and bridges to precipitation extremes. Transport infrastructure on ice or permafrost is especially vulnerable. {10.4}

Climate change will affect tourism resorts, particularly ski resorts, beach resorts, and nature resorts (*robust evidence*, *high agreement*) and tourists may spend their holidays at higher altitudes and latitudes (*medium evidence*, *high agreement*). The economic implications of climate change-induced changes in tourism demand and supply entail gains for countries closer to the poles and higher up the mountains and losses for other countries. The demand for outdoor recreation is affected by weather and climate, and impacts will vary geographically and seasonally. {10.6}

Climate change will affect insurance systems (*robust evidence*, *high agreement*). More frequent and/or intensive weather disasters as projected for some regions/hazards will increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in low- and middle-income countries. Economic-vulnerability reduction through insurance has proven effective. Large-scale public-private risk prevention initiatives and government insurance of the non-diversifiable portion of risk offer example mechanisms for adaptation. Commercial reinsurance and risk-linked securitization markets also have a role in ensuring financially resilient insurance and risk transfer systems. {10.7}

Climate change will affect the health sector (*medium evidence*, *high agreement*) through increases in the frequency, intensity, and extent of extreme weather events as well as increasing demands for health care services and facilities, including public health programs, disease prevention activities, health care personnel, infrastructure, and supplies related to treatment of infectious diseases and temperature-related events. {10.8}

Well-functioning markets provide an additional mechanism for adaptation and thus tend to reduce negative impacts and increase positive ones for any specific sector or country (*medium evidence*, *high agreement*). The impacts of climate on one sector of the economy of one country in turn affect other sectors and other countries though product and input markets. Markets increase overall welfare, but not necessarily welfare in every sector and country. {10.9}

The impacts of climate change may decrease productivity and economic growth, but the magnitude of this effect is not well understood (*limited evidence*, *high agreement*). Climate could be one of the causes why some countries are trapped in poverty, and climate change may make it harder to escape poverty. {10.9}

Global economic impacts from climate change are difficult to estimate. Economic impact estimates completed over the past 20 years vary in their coverage of subsets of economic sectors and depend on a large number of assumptions, many of which are disputable, and many estimates do not account for catastrophic changes, tipping points, and many other factors. With these recognized limitations, the incomplete estimates of global annual economic losses for additional temperature increases of ~2°C are between 0.2 and 2.0% of income (±1 standard deviation around the mean) (*medium evidence*, *medium agreement*). Losses are *more likely than not* to be greater, rather than smaller, than this range (*limited evidence*, *high agreement*). Additionally, there are large differences between and within countries. Losses accelerate with greater warming (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. Estimates of the incremental economic impact of emitting carbon dioxide lie between a few dollars and several hundreds of dollars per tonne of carbon (*robust evidence*, *medium agreement*). Estimates vary strongly with the assumed damage function and discount rate. {10.9}

Not all key economic sectors and services have been subject to detailed research. Few studies have evaluated the possible impacts of climate change on mining, manufacturing, or services (apart from health, insurance, and tourism). Further research, collection, and access to more detailed economic data and the advancement of analytic methods and tools will be required to assess further the potential impacts of climate on key economic systems and sectors. {10.5, 10.8, 10.10}

10.1. Introduction and Context

This chapter discusses the implications of climate change on key economic sectors and services, for example, economic activity. Other chapters discuss impacts from a physical, chemical, biological, or social perspective. Economic impacts cannot be isolated; therefore, there are a large number of cross-references to sections in other chapters of this report. In some cases, particularly agriculture, the discussion of the economic impacts is integrated with the other impacts.

Focusing on the potential impact of climate change on economic activity, this chapter addresses questions such as: How does climate change affect the demand for a particular good or service? What is the impact on its supply? How do supply and demand interact in the market? What are the effects on producers and consumers? What is the effect on the overall economy, and on welfare?

An inclusive approach was taken, discussing all sectors of the economy. Section SM10.1 found in this chapter's on-line supplementary material shows the list of sectors according to the International Standard Industrial Classification. This assessment reflects the breadth and depth of the state of knowledge across these sectors; many of which have not been evaluated in the literature. We extensively discuss five sectors: energy (Section 10.2), water (Section 10.3), transport (Section 10.4), tourism (Section 10.6), and insurance (Section 10.7). Other primary and secondary sectors are discussed in Section 10.5, and Section 10.8 is devoted to other service sectors. Food and agriculture is addressed in Chapter 7. Sections 10.2 through 10.8 discuss individual sectors in isolation. Markets are connected, however. Section 10.9 therefore assesses the implications of changes in any one sector on the rest of the economy. It also discusses the effect of the impacts of climate change on economic growth and development. Chapter 19 assesses the impact of climate change on economic welfare—that is, the sum of changes in consumer and producer surplus, including for goods and services not traded within the formal economy. This is not attempted here. The focus is on economic activity. Section 10.10 discusses whether there may be vulnerable sectors that have yet to be studied.

Previous assessment reports by the IPCC did not have a chapter on "key economic sectors and services." Instead, the material assembled here was spread over a number of chapters. The Fourth Assessment Report (AR4) is referred to in the context of the sections below. In some cases, however, the literature is so new that previous IPCC reports did not discuss these impacts at any length.

10.2. Energy

Studies conducted since AR4 and assessed here confirm the main insights about the impacts of climate change on energy demand as reported in the Second Assessment Report (SAR; Acosta et al., 1995) and reinforced by the Third Assessment Report (TAR; Scott et al., 2001) and AR4 (Wilbanks et al., 2007): ceteris paribus, in a warming world, energy demand for heating will decline and energy demand for cooling will increase; the balance of the two depends on the geographic, socioeconomic, and technological conditions. The relative importance of temperature changes among the drivers of energy demand varies across regions and will change over time. Earlier IPCC assessments did not write much about energy supply, but an increasing number of studies now explore its vulnerability, impacts, and adaptation options (Karl et al., 2009; Troccoli, 2010; Ebinger and Vergara, 2011). The energy sector will be transformed by climate policy (WGIII AR5 Chapter 7) but impacts of climate changes too will be important for secure and reliable energy supply.

10.2.1. Energy Demand

Most studies conducted since AR4 explore the impacts of climate change on residential energy demand, particularly electricity (Mideksa and Kallbekken, 2010). Some studies encompass the commercial sector as well but very few deal with industry and agriculture. In addition to a few global studies based on global energy or integrated assessment models, the new studies tend to focus on specific countries or regions (Zachariadis, 2010; Olonscheck et al., 2011), rely on improved methods (more advanced statistical techniques; de Cian et al., 2013) and data (both

Frequently Asked Questions

FAQ 10.1 | Why are key economic sectors vulnerable to climate change?

Many key economic sectors are affected by long-term changes in temperature, precipitation, sea level rise, and extreme events, all of which are impacts of climate change. For example, energy is used to keep buildings warm in winter and cool in summer. Changes in temperature would thus affect energy demand. Climate change also affects energy supply through the cooling of thermal plants, through wind, solar, and water resources for power, and through transport and transmission infrastructure. Water demand increases with temperature but falls with rising carbon dioxide (CO_2) concentrations as CO_2 fertilization improves the water use efficiency plant respiration. Water supply depends on precipitation patterns and temperature, and water infrastructure is vulnerable to extreme weather, while transport infrastructure is designed to withstand a particular range of weather conditions, and climate change would expose this infrastructure to weather outside historical design criteria. Recreation and tourism are weather-dependent. As holidays are typically planned in advance, tourism depends on the *expected* weather and will thus be affected by climate change. Health care systems are also impacted, as climate change affects a number of diseases and thus the demand for and supply of health care.

historical and regional climate projections), and many of them explicitly include non-climatic drivers of energy demand (e.g., sources). A few studies consider changes in demand together with changes in climate-dependent energy sources, such as hydropower (Hamlet et al., 2010).

Sorting the assessed studies according to the present climate (represented by mean annual temperature based on 1971–2000 climatology) and current income (represented by gross domestic product (GDP) per capita in 2009), the general patterns are as follows. In countries and regions with already high incomes, climate-related changes in energy demand will be driven primarily by increasing temperatures. In countries/regions with high incomes and warm climates, increasing temperatures will be associated with heavier use of air conditioning. In countries/regions with high incomes and temperate and cold climates, increasing temperatures will result in lower demands for various energy forms (electricity, gas, coal, oil). Increasing incomes will play a marginal role in these countries and regions. In contrast, changes in income will be the main driver of increasing demand for energy (mainly electricity for air conditioning and transportation fuels) in present-day low-income countries in warm climates. Neither indicator is ideal because country-level mean annual temperatures for large countries can hide large regional differences and average incomes may conceal large disparities, but they help cluster the national and regional studies in the search for general finding.

At the global scale, energy demand for residential air conditioning in summer is projected to increase rapidly in the 21st century under the reference climate change scenario (medium population and economic growth globally, but faster economic growth in developing countries; no mitigation policies in addition to those in place in 2008) by the Targets IMAGE Energy Regional Model/Integrated Model to Assess the Global Environment (TIMER/IMAGE) model (Isaac and Van Vuuren, 2009). The increase is from nearly 300 TWh in 2000 to about 4000 TWh in 2050 and more than 10,000 TWh in 2100, about 75% of which is due to increasing income in emerging market countries and 25% is due to climate change. Energy demand for heating in winter increases too, but much less rapidly, since in most regions with the highest need for heating, incomes are already high enough for people to heat their homes to the desired comfort level (except in some poor households). In these regions, energy demand for heating will decrease.

These general patterns and especially the quantitative results of the projected shifts in energy and electricity demand can be modified by many other factors. In addition to changes in temperatures and incomes, the actual energy demand will be influenced by changes in demographics (upward by increasing population and decreasing average household size, mixed effects from urbanization), lifestyles (upward by larger floor area of dwellings), building codes and regulations for the design and insulation of the housing stock, the energy efficiency of heating/cooling devices, the abundance and energy efficiency of other electric household appliances, the price of energy, and so forth.

10.2.2. Energy Supply

Changes in climate attributes (temperature, precipitation, windiness, cloudiness, etc.) will affect different energy sources and technologies differently. Gradual climate change will progressively affect the operation of energy installations and infrastructure over time. Possible changes in the frequency and intensity of extreme weather events (EWEs) as a result of climate change represent a different kind of hazard for them. (EWEs are weather events that are rare at a particular place and time of the year; they are usually defined as rare or rarer than the 10th and 90th percentiles of a probability density function estimated from observations; see Glossary). Rummukainen (2013) and Mika (2013) summarize recent trends and prospects relevant for the energy sector. This section assesses the most important impacts and adaptation options in both categories. Table 10-1 provides an overview.

Currently, thermal power plants provide about 80% of global electricity and their share is projected to remain high in most mitigation scenarios (IEA, 2010a). Thermal power plants can be designed to operate under diverse climatic conditions, from the cold Arctic to the hot tropical regions and are normally well adapted to the prevailing conditions. However, they might face new challenges and will need to respond by hard (design or structural methods) or soft (operating procedures) measures as a result of climate change.

A general impact of climate change on thermal power generation (including combined heat and power) is the decreasing efficiency of thermal conversion as a result of rising temperature that cannot be offset per se. Yet there is much room to improve the efficiency of currently operating subcritical steam power plants (IEA, 2010b). As new materials allow higher operating temperatures in coal-fired power plants (Gibbons, 2012), supercritical and ultra-supercritical steam-cycle plants (operating at much higher pressure and temperature conditions than conventional power plants) will reach even higher efficiency that can more than compensate the efficiency losses due to higher temperatures. Yet in the absence of climate change, these efficiency gains from improved technology would reduce the costs of energy, so there is still a net economic loss due to climate change. Another problem facing thermal power generation in many regions is the decreasing volume and increasing temperature of water for cooling, leading to reduced power generation, operation at reduced capacity, and even temporary shutdown of power plants (Ott and Richter, 2008; Hoffmann et al., 2010; IEA, 2012; Sieber, 2013). Both problems will be exacerbated if carbon dioxide (CO_2) capture and handling equipment is added to fossil-fired power plants: energy efficiency declines by 8 to 14% (IPCC, 2005) and water requirement per MWh electricity generated can double (Macknick et al., 2011). Using partial equilibrium river basin models, (Hurd et al., 2004; Strzepek et al., 2013) estimate USA welfare loses due to thermal cooling water changes at US$622 million per year up to 2100, a 6.5% welfare loss in the energy sector. Van Vliet et al. (2012) find that the southeastern United States, Europe, eastern China, southern Africa, and southern Australia could potentially be affected by reduced water available for thermoelectric power and drinking water, inducing changes to dry or hybrid cooling (with concomitant loss in electric output), or plant shut downs, with associated impacts on local and regional economic activity.

Adaptation possibilities range from relatively simple and low-cost options such as exploiting non-traditional water sources and re-using process water to measures such as installing dry cooling towers, heat pipe exchangers, and regenerative cooling (Ott and Richter, 2008; De Bruin et al., 2009), all which increase costs. Water use regulation, heat

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Table 10-1 | Main projected impacts of climate change and extreme weather events on energy supply and the related adaptation options.

Technology	Changes in climatic or related attributes	Possible impacts	Adaptation options
Thermal and nuclear power plants	Increasing air temperature	Reduces efficiency of thermal conversion by 0.1–0.2% in the USA; by 0.1–0.5% in Europe, where the capacity loss is estimated in the range of 1–2% per 1°C temperature increase, accounting for decreasing cooling efficiency and reduced operation level/shutdown	Siting at locations with cooler local climates where possible
	Changing (lower) precipitation and increasing air temperature increases temperature and reduces the availability of water for cooling.	Less power generation; annual average load reduction by 0.1–5.6% depending on scenario	Use of non-traditional water sources (e.g., water from oil and gas fields, coal mines and treatment, treated sewage); re-use of process water from flue gases (can cover 25–37% of the power plant's cooling needs), coal drying, condensers (drier coal has higher heating value, cooler water enters cooling tower), flue-gas desulfurization; using ice to cool air before entering the gas turbine increases efficiency and output, melted ice used in cooling tower; condenser mounted at the outlet of cooling tower to reduce evaporation losses (by up to 20%). Alternative cooling technologies: dry cooling towers, regenerative cooling, heat pipe exchangers; costs of retrofitting cooling options depend on features of existing systems, distance to water, required additional equipment, estimated at US$250,000–500,000 per megawatt
	Increasing frequency of extreme hot temperatures	Exacerbating impacts of warmer conditions: reduced thermal and cooling efficiency; limited cooling water discharge; overheating buildings; self-ignition of coal stockpiles	Cooling of buildings (air conditioning) and of coal stockpiles (water spraying)
	Drought: reduced water availability	Exacerbating impacts of warmer conditions, reduced operation and output, shutdown	Same as reduced water availability under gradual climate change
Hydropower	Increase/decrease in average water availability	Increased/reduced power output	Schedule release to optimize income
	Changes in seasonal and inter-annual variation in inflows (water availability)	Shifts in seasonal and annual power output; floods and lost output in the case of higher peak flows	Soft: adjust water management Hard: build additional storage capacity, improve turbine runner capacity
	Extreme precipitation causing floods	Direct and indirect (by debris carried from flooded areas) damage to dams and turbines, lost output due to releasing water through bypass channels	Soft: adjust water management Debris removal Hard: increase storage capacity
Solar energy	Increasing mean temperature	Improving performance of TH (especially in colder regions), reducing efficiency of PV and CSP with water cooling; PV efficiency drops by ~0.5% per 1°C temperature increase for crystalline silicon and thin-film modules as well, but performance varies across types of modules, with thin film modules performing better; long-term exposure to heat causes faster aging.	
	Changing cloudiness	Increasing unfavorable (reduced output), decreasing beneficial (increased output) for all types, but evacuated tube collectors for TH can use diffuse insolation. CSP more vulnerable (cannot use diffuse light)	Apply rougher surface for PV panels that use diffuse light better; optimize fixed mounting angle for using diffuse light, apply tracking system to adjust angle for diffuse light conditions; install/increase storage capacity
	Hot spells	Material damage for PV, reduced output for PV and CSP; CSP efficiency decreases by 3–9% as ambient temperature increases from 30 to 50°C and drops by 6% (tower) to 18% (trough) during the hottest 1% of time	Cooling PV panels passively by natural air flows or actively by forced air or liquid coolants
	Hail	Material damage to TH: evacuated tube collectors are more vulnerable than flat plate collectors. Fracturing as glass plate cover, damage to photoactive material	Flat plate collectors: using reinforced glass to withstand hailstones of 35 mm (all of 15 tested) or even 45 mm (10 of 15 tested); only 1 in 26 evacuated tube collectors withstood 45-mm hailstones. Increase protection to current standards or beyond them
Wind power	Windiness: total wind resource (multi-year annual mean wind power densities); likely to remain within ±50% of current values in Europe and North America; within ±25% of 1979–2000 historical values in contiguous USA	Change in wind power potential	Site selection
	Wind speed extremes: gust, direction change, shear	Structural integrity from high structural loads; fatigue, damage to turbine components; reduced output	Turbine design, lidar-based protection

Notes: CSP = concentrating solar power; PV = photovoltaic; TH = thermal heating.

Sources: EPA (2001); Parkpoom et al. (2005); Norton (2006); Pryor et al. (2006); Walter et al. (2006); Christensen and Busuioc (2007); DOE (2007); NETL National Energy Technology Laboratory (2007); Schaefli et al. (2007); Bloom et al. (2008); Feeley III et al. (2008); Haugen and Iversen (2008); Leckebusch et al. (2008); Markoff and Cullen (2008); Ott and Richter (2008); Sailor et al. (2008); Droogers (2009); Förster and Lilliestam (2009); Honeyborne (2009); Kurtz et al. (2009); SPF (2009); Hoffmann et al. (2010); Pryor and Barthelmie (2010, 2011, 2013); Pryor and Schoof (2010); Kurtz et al. (2011); Linnerud et al. (2011); Mukheibir (2013); Patt et al. (2013); Sieber (2013); Williams (2013).

discharge restrictions, and occasional exemptions might be an institutional adaptation (Eisenack and Stecker, 2012). Though it is easier to plan for changing climatic conditions and select the site and the conforming cost-efficient cooling technology for new builds, response options are more limited for existing power plants, especially for those toward the end of their economic lifetime.

Climate change impacts on thermal efficiency and cooling water availability affect nuclear power plants as well but the safety regulations are stricter than for fossil-fired plants (Williams and Toth, 2013). A range of alternative cooling options are available to deal with water deficiency, ranging from re-using wastewater and recovering evaporated water (Feeley III et al., 2008) to installing dry cooling (EPA, 2001).

The implications of EWEs for nuclear plants can be severe if not properly addressed. Reliable interconnection (on-site power and instrumentation connections) of intact key components (reactor vessel, cooling equipment, control instruments, back-up generators) is indispensable for the safe operation and/or shutdown of a nuclear reactor. For most of the existing global nuclear fleet, a reliable connection to the grid for power to run cooling systems and control instruments in emergency situations is another crucial item (IAEA, 2011). Several EWEs can damage the components or disrupt their interconnections. Preventive and protective measures include technical and engineering solutions (circuit insulation, shielding, flood protection) and adjusting operation to extreme conditions (reduced capacity, shutdown) (Williams and Toth, 2013).

Hydropower is by far the largest of renewable energy sources in the current electricity mix. It is projected to remain important in the future, irrespective of the climate change mitigation targets in many countries (IEA, 2010a,b). The resource base of hydropower is the hydrologic cycle driven by prevailing climate and topology. The former makes the resource base and hence hydropower generation highly dependent on future changes in climate and related changes in extreme weather events (Ebinger and Vergara, 2011; Mukheibir, 2013).

Assessing the impacts of climate change on hydropower generation is highly complex. A series of nonlinear and region-specific changes in mean annual and seasonal precipitation and temperatures, the resulting evapotranspiration losses, shifts in the share of precipitation falling as snow and the timing of its release from high elevation, and the climate response of glaciers make resource estimates difficult (see Chapters 2 and 3) while regional changes in water demand due to changes in population and economic activities (especially irrigation demand for agriculture) present competition for water resources that are hard to project (see Section 10.3). Further complications stem from the possibly increasing need to combine hydropower generation with changing flood control and ecological (minimum dependable flow) objectives induced by changing climate regimes. For hydropower locations, adaption to climate change to maintain output has been reported; in Ethiopia, Block and Strzepek (2012) report that capital expenditures through 2050 may either decrease by approximately 3% under extreme wet scenarios or increase by up to 4% under a severe dry scenario. In the Zambezi river basin, hydropower may fall by 10% by 2030, and by 35% by 2050 under the driest scenario (Strzepek et al., 2012). Lower generation is likely in the upstream power stations of the Zambezi basin and increases are *likely* downstream (Fant et al., 2013).

Focusing on the possible impacts of climate change on hydroelectricity and the adaptation options in the sector in response to the changes in the amount, the seasonal and interannual variations of available water, and in other demands, the conclusion from the literature is that the overall impacts of climate change and EWEs on hydropower generation by 2050 is expected to be slightly positive in most regions (e.g., in Asia, by 0.27%) and negative in some (e.g., in Europe, by –0.16%), with diverging patterns across regions, watersheds within regions, and even river basins within watersheds (IPCC, 2011). Adaptation responses and planning tools for long-term hydrogeneration may need to be enhanced to cope with slow but persistent shifts in water availability. Short-term management models may need to be enhanced to deal with the impacts of EWEs. A series of hard (raising dam walls, adding bypass channels) and soft (adjusting water release) measures are available to protect the related infrastructure (dams, channels, turbines, etc.) and optimize incomes by timing generation when electricity prices are high (Mukheibir, 2013).

Solar energy is expected to increase from its currently small share in the global energy balance across a wide range of mitigation scenarios (IEA, 2008, 2009, 2010a,b). The three main types of technologies for harnessing energy from insolation include thermal heating (TH; by flat plate, evacuated tube, and unglazed collectors), photovoltaic (PV) cells (crystalline silicon and thin film technologies), and concentrating solar power (CSP; power tower and power trough producing heat to drive a steam turbine for generating electricity). The increasing body of literature exploring the vulnerability and adaptation options of solar technologies to climate change and EWEs is reviewed by Patt et al. (2013).

All types of solar energy are sensitive to changes in climatic attributes that directly or indirectly influence the amount of insolation reaching them. If cloudiness increases under climate change (WGI AR5 Chapters 11, 12), the intensity of solar radiation and hence the output of heat or electricity would be reduced. Efficiency losses in cloudy conditions are less for technologies that can operate with diffuse light (evacuated tube collectors for TH, PV collectors with rough surface). Since diffuse light cannot be concentrated, CSP output would cease under cloudy conditions but the easy and relatively inexpensive possibility to store heat reduces this vulnerability if sufficient volume of heat storage is installed (Khosla, 2008; Richter et al., 2009).

The exposure of sensitive material to harsh weather conditions is another source of vulnerability for all types of solar technologies. Windstorms can damage the mounting structures directly and the conversion units by flying debris, whereby technologies with smaller surface areas are less vulnerable. Hail can also cause material damage and thus reduced output and increased need for repair. Depending on regional conditions, strong wind can deposit sand and dust on the collector's surface, reducing efficiency and increasing the need for cleaning.

Climate change and EWE hazards per se do not pose any particular constraints for the future deployment of solar technologies. Technological development continues in all three solar technologies toward new designs, models, and materials. An objective of these development efforts is to make the next generation of solar technologies less vulnerable to existing physical challenges, changing climatic conditions, and the impacts of EWEs. Technological development also results in a diverse portfolio of models to choose from according to the climatic and weather characteristics of the deployment site. These development efforts can be integrated in addressing the key challenge for solar technologies today: reducing the costs.

Harnessing wind energy for power generation is an important part of the climate change mitigation portfolio in many countries. Assessing the possible impacts of climate change and EWEs and identifying possible adaptation responses for wind energy is complicated by the complex dynamics characterizing this generation source. Relevant attributes of climate are expected to change; the technology is evolving (blade design, other components); see Kong et al. (2005) and Barlas and Van Kuik (2010); there is an increasing deployment offshore and a transition to larger turbines (Garvey, 2010) and to larger sites (multi megawatt arrays) (Barthelmie et al., 2008).

The key question concerning the impacts of a changing climate regime on wind power is related to the resource base: how climate change will rearrange the temporal (inter- and intra-annual variability) and spatial (geographical distribution) characteristics of the wind resource. In the next few decades, wind resources (measured in terms of multi-annual wind power densities) are estimated to remain within the ±50% of the mean values over the past 20 years in Europe and North America (Pryor and Barthelmie, 2010). The wide range of the estimates results from the circulation and flow regimes in different General Circulation Models (GCMs) and Regional Climate Models (RCMs) (Bengtsson et al., 2006; Pryor and Barthelmie, 2010). A set of four GCM-RCM combinations for the period 2041–2062 indicates that average annual mean energy density will be within ±25% of the 1979–2000 values in all 50-km grid cells over the contiguous USA (Pryor et al., 2011; Pryor and Barthelmie, 2013). Yet, little is known about changes in the interannual, seasonal, or diurnal variability of wind resources.

Wind turbines already operate in diverse climatic and weather conditions. As shown in Table 10-1, siting, design, and engineering solutions are available to cope with various impacts of gradual changes in relevant climate attributes over the coming decades. The requirements to withstand extreme loading conditions resulting from climate change are within the safety margins prescribed in the design standards, although load from combinations of extreme events may exceed the design thresholds (Pryor and Barthelmie, 2013). In summary, the wind energy sector does not face insurmountable challenges resulting from climate change.

In the coal fuel cycle, vulnerability in mining depends on mining method. Surface mining might be particularly affected by high precipitation extremes and related floods and erosion, and temperature extremes, especially extreme cold that might encumber extraction for some time, whereas impacts on coal cleaning and operation of underground mines will probably be less severe (Ekman, 2013). Changes in drainage and runoff regulation for on-site coal storage as well as in coal handling might be required due to the increased moisture content of coal and more energy might be required for coal drying before transportation (CCSP, 2007). At the back end of the fuel cycle, the management of fly-ash, bottom ash, and boiler slag may need to be modified in response to changes in some EWE patterns such as wind, precipitation, and floods. Impacts on biomass-based energy sources are discussed in Chapter 7 of this report.

Climate- and weather-related hazards in the oil and gas sector include tropical cyclones with potentially severe effects on offshore platforms and onshore infrastructure as well, leading to more frequent production interruptions and evacuation (Cruz and Krausmann, 2013). Gradual changes in air temperature and precipitation are projected to generate risk and opportunities for the oil and gas industry. For example, new areas for oil and gas exploration could open in the Arctic, potentially increasing the technically recoverable resource base (Cruz and Krausmann, 2013). Reduced sea ice thickness and coverage might open new shipping routes, thus reducing shipping costs, while ice scour and ice pack loading on marine structures would increase. However, most changes involve increased risks, such as thawing permafrost would increase construction costs on unstable ground relative to ice-based construction, while thaw subsidence would trigger increased maintenance costs. Sea level rise (SLR) and coastal erosion would degrade coastal barriers, damage facilities, and trigger relocation (Dell and Pasteris, 2010).

10.2.3. Transport and Transmission of Energy

Primary energy sources (coal, oil, gas, uranium), secondary energy forms (electricity, hydrogen, warm water), and waste products (CO_2, coal ash, radioactive waste) are transported in diverse ways to distances ranging from a few to thousands of kilometers. The transport of energy-related materials by ships (ocean and inland waters), rail, and road are exposed to the same impacts of climate change as the rest of the transport sector (see Section 10.4). This subsection deals only with transport modes that are unique to the energy sector (power grid) or predominantly used by it (pipelines). Table 10-2 provides an overview of the impacts of climate change and EWEs on energy transmission, together with the options to reduce vulnerability.

Pipelines play a central role in the energy sector by transporting oil and gas from the wells to processing and distributing centers to distances from a few hundred to thousands of kilometers. With the potential spread of CO_2 capture and storage (CCS) technology, another important function will be to deliver CO_2 from the capture site (typically fossil power plants) to the storage site onshore or offshore. Pipelines have been operated for over a century in diverse climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. This implies that technological solutions are available for the construction and operation of pipelines under diverse geographical and climatic conditions. Yet adjustments may be needed in existing pipelines and improvements in the design and deployment of new ones in response to the changing climate and weather conditions.

In addition to reduced line-heating and dilution needs due to reduced viscosity of liquid fuels under warmer temperatures, pipelines will be affected mainly by secondary impacts of climate change: SLR in coastal regions, melting permafrost in cold regions, floods washing away infrastructure, landslides triggered by heavy rainfall, and bushfires caused by heat waves or extreme temperatures in hot regions. A proposed way to reduce vulnerability to these events is to amend land zoning codes, risk-based design, and construction standards for new pipelines, and structural upgrades to existing infrastructure (Antonioni et al., 2009; Cruz and Krausmann, 2013).

Table 10-2 | Main impacts of climate change and extreme weather events on pipelines and the electricity grid.

Technology	Changes in climatic or related attribute	Impacts	Adaptation options
Pipelines	Melting permafrost	Destabilizing pillars, obstructing access for maintenance and repair	Adjust design code and planning criteria, install disaster mitigation plans
	Increasing high wind, storms, hurricanes	Damage to offshore and onshore pipelines and related equipment, spills; lift and blow heavy objects against pipelines, damage equipment	Enhance design criteria, update disaster preparedness
	Flooding caused by heavy rain, storm surge, or sea level rise	Damage to pipelines, spills	Siting (exclude flood plains), waterproofing
Electricity grid	Increasing average temperature	Increased transmission line losses	Include increasing temperature in the design calculation for maximum temperature/rating
	Increasing high wind, storms, hurricanes	Direct mechanical damage to overhead lines, towers, poles, substations, flashover caused by live cables galloping and thus touching or getting too close to each other; indirect mechanical damage and short circuit by trees blown over or debris blown against overhead lines	Adjust wind loading standards, reroute lines alongside roads or across open fields; manage vegetation; improve storm and hurricane forecasting
	Extreme high temperatures	Lines and transformers may overheat and trip off; flashover to trees underneath expanding cable	Increase system capacity, increase tension in the line to reduce sag, add external coolers to transformers
	Combination of low temperature, wind and rain, ice storm	Physical damage (including collapse) of overhead lines and towers caused by ice build-up on them	Enhance design standard to withstand larger ice and wind loading, reroute lines alongside roads or across open fields; improve forecasting of ice storms impacts on overhead lines and on transmission circuits

Sources: Bayliss (1996); Krausmann and Mushtaq (2008); Reed (2008); Hines et al. (2009); Winkler et al. (2010); Vlasova and Rakitina (2010); McColl (2012); Cruz and Krausmann (2013); Ward (2013).

Owing to the very function of the electricity grid to transmit power from generation units to consumers, the bulk of its components (overhead lines, substations, transformers) are located outdoors and exposed to EWE. The power industry has developed numerous technical solutions and related standards to protect assets and provide reliable electricity supply under existing climate and weather conditions worldwide. However, these assets and the reliability of supply may be vulnerable to changes in the frequency and intensity of EWEs under changing climate conditions (DOE, 2013). Higher average temperatures increase transmission efficiency and reduce current carrying capacity, but this effect is relatively small compared to the physical and monetary damages that can be caused by EWEs (Ward, 2013). Historically, high wind conditions, including storms, hurricanes, and tornados, have been the most frequent cause of grid disruptions (mainly due to damages to the distribution networks); and more than half of the damage was caused by trees (Reed, 2008). Other impacts include freezing precipitation, ice and winter storms, wildfires caused by higher temperatures, less precipitation, and increased tree death caused by pests. If the frequency and power of high wind conditions, as well as extreme precipitation events, will increase in the future, vegetation management along existing power lines, and rerouting new transmission lines along roads or across open fields or moving them underground might help reduce related risks. An important institutional option is to redefine technical standards to provide incentives for grid operators to implement appropriate adaptation measures. Such measures are less expensive to implement as part of the maintenance-renewal cycle than as independent retrofit measures.

The economic importance of a reliable transmission and distribution network is highlighted by the fact that the damage to customers tends to be much higher than the price of electricity not delivered (lost production, electricity enabled commerce, service delivery, food spoilage, lost or restricted water availability). Losses can be minimized through efficient rationing of electricity (de Nooij et al., 2009) if generation is the limiting factor. Designing and building climate-resilient infrastructure will depend on technical standards, market governance, and the type and degree of liberalization and deregulation of grid services.

10.2.4. Macroeconomic Impacts

Most economic research related to climate change impacts on the energy sector has focused on mitigation rather than the economic implications of climate change itself. Table 10-3 summarizes the recent studies on the economic implications of climate change and extreme weather impacts in the energy sector.

Assessing across a broad array of studies that focus on different regions and regional divisions, examine different climate change impacts, include a different mix of sectors, model different time frames, make different assumptions about adaptation, and employ different types of models with different output metrics leads to the overall conclusion that the macroeconomic impact of climate change on energy demand is *likely* to be minimal in developed countries (Bosello et al., 2007a, 2009; Aaheim et al., 2009; Jochem et al., 2009; Eboli et al., 2010).

The current literature sheds less light on the implications for developing countries and on other climate impacts in the energy sector beyond those related to changes in energy demand. Europe is the focus of most of the literature so far. Only two studies focus on developing countries: Mexico and Brazil (Boyd and Ibarraran, 2009; de Lucena et al., 2010). Asia and Africa are not well represented, appearing as aggregated regions in only three global studies (Bosello et al., 2007a, 2009; Eboli et al., 2010). The limited results indicate that developing countries *likely* face a greater negative GDP impact with respect to climate change implications for the energy sector than developed countries, largely because of higher expected temperature changes (Aaheim et al., 2009; Boyd and Ibarraran, 2009; Eboli et al., 2010).

Table 10-3 | Economy-wide implications of impacts of climate change and extreme weather on the energy sector.

Study	Model type	Climate impacts modeled	Energy/economic impacts	Regions	Sectors studied
Bosello et al. (2009)	IAM	Rising temperatures/changing demand for energy; impacts from four other sectors/events (Global, 2001–2050)	Change in gross domestic product (GDP) in 2050 due to rising temperatures and changing energy demand: 0–0.75% (+1.2°C); –0.1% to 1.2% (+3.1°C)	14	4
Jorgenson et al. (2004)	CGE	Rising temperatures/changing demand for energy; climate impacts from three other sectors (USA, 2000–2100)	Optimistic adaptation: 4–6.7% higher energy productivity per year (2000–2100) Output from electricity: –6% in 2050; GDP is +0.7% (aggregate all sectors, average annual 2000–2100) Pessimistic adaptation: 0.5–2.2% lower energy productivity per year Output from electricity: +2% in 2050; GDP is –0.6% (aggregate impact all sectors)	1	35
Bosello et al. (2007a)	CGE	Rising temperatures/changing demand for energy (Global, 2050)	Change in GDP in 2050 (perfect competition): –0.297% to 0.027% Change in GDP in 2050 (imperfect competition): –0.303% to 0.027%	8	1
Aaheim et al. (2009)	CGE	Change in precipitation affects share of hydroelectric power; rising temperatures/changing demand for energy; impacts from four other sectors (Western Europe, 2071–2100)	Impact from all sectors in 2100: GDP in cooler regions: –1% to –0.25% GDP in warmer regions: –3% to –0.5% Adaptation can mitigate 80–85% of economic impact	8	11
Boyd and Ibarraran (2009)	CGE	Drought scenario affecting hydroelectric plus three other sectors (Mexico, 2005–2026)	• Generation output in 2026: –2.1% • Refining output: –10.1% • Coal output: –7.8% • NG output: –2% • Crude oil output: +1.7% • GDP: –3% With adaptation: • Generation output in 2026: 0.24% • Refining output: 1.36% • Coal output: 1.09% • NG output: 0.34% • Crude oil output: 0.22% • GDP: 0.33%	1	2
Jochem et al. (2009)	PE/CGE	Rising temperatures/changing demand for energy; change in technical potential of renewables; change in rainfall induces change in hydroelectric production; high temperatures induce water temperatures exceeding regulatory limits (Europe); high temperatures induce greater electric grid losses and lower thermal efficiency; generic extreme events induce reduced capital stock in CGE model (EU27+2, 2005–2050)	• GDP (Europe): –50 billion € p.a. in 2035 • GDP (Europe): –240 billion € p.a. in 2050 • GDP (EU regions): –0.1% to –0.4% in 2035 • GDP (EU regions): –0.6% to –1.3% in 2050 • Jobs (Europe): –380K in 2035 • Jobs (Europe): –1 million in 2050	25	1
Eboli et al. (2010a)	CGE	Rising temperatures/changing demand for energy; climate impacts in four other sectors modeled (Global, 2002–2100)	By 2100, change in GDP due to climate impacts on energy demand vary by country between about –0.15% and 0.7%. USA and Japan were negative and all other countries positive. Overall economic impact from all sectors is neutral to positive for developed countries and negative for developing ones.	8	17
Golombek et al. (2011)	PE	Rising temperatures/changing demand for energy; rising temperatures/reduced thermal efficiency; change in water inflow (Western Europe, 2030)	Net impact on the price of electricity is a 1% increase. Generation decreases by 4%.	13	4
de Lucena et al. (2010)	PE	Changing precipitation induces change in hydroelectric production; rising temperatures induce lower NG thermal efficiency; rising temperatures induce change in demand for energy (Brazil, 2010–2035)	New generating capacity needed to produce additional 153–162 TWh per year. Capital investment of US$48–51 billion, which is equivalent to 10 years of capital expenditures in Brazil's long-term energy plan. US$6.9–7.2 billion in additional annual operating expenses for each year in which worst-case hydroelectric production occurs	1	11
Bye et al. (2008)	PE	Water shortages (Nordic countries, hypothetical 2-year period)	Water shortage scenarios can lead to a 100% increase in electricity prices at peak demand over a 2-year period. Higher prices lead to marginal reductions in demand (about 1–2.25%).	4	1
Koch et al. (2012)	PE	High temperatures induce water temperatures exceeding regulatory limits (Berlin, 2010–2050)	Thermal plant outages amounting to 60 million € for plants in Berlin through 2050	1	1
Gabrielsen et al. (2005)	Econometric	Rising temperatures/changing demand for energy; change in water inflow; change in wind speeds (Nordic countries, 2000–2040)	Net change in electricity supply in 2040: 1.8% Change in electricity demand: 1.4% Change in electricity price: –1.0%	4	1

Table 10-3 (continued)

Study	Model type	Climate impacts modeled	Energy/economic impacts	Regions	Sectors studied
UNDP (2011)	PE	Damage Case 1 (DC1): hotter in both winter and summer—decreased demand for heating and increased demand for cooling; Damage Case 2 (DC2): colder in both winter and summer—increased demand for heating and decreased demand for cooling; Damage Case 3 (DC3): colder in the winter and hotter in the summer—increased demand for heating and increased demand for cooling (Macedonia, 2009–2030)	Change in electricity demand in residential and commercial sectors: • DC1: 3.5% • DC2: 0.3% • DC3: 8% Change in electricity system cost: • DC1: 0.8% • DC2: 0.06% • DC3: 1.74%	9	5
DOE (2009)	PE	Drought scenario (Western Electric Coordinating Council, USA, 2010–2020)	In 2020, 3.7% reduction in coal generation; 43.4% increase in NG generation; 29.3% reduction in hydroelectric generation. Production cost increase of US$3.5 billion. Average monthly electricity prices up 8.1% (Nov) to 24.1% (July)	1	1

Note: The regions indicated in the Regions column vary in size and are model-specific. CGE = Computable General Equilibrium; PE = Partial Equilibrium; IAM = Integrated Assessment Model.

Despite the considerable number of potential climate change and extreme weather phenomena—higher mean temperatures, changes in rainfall patterns, changes in wind patterns, changes in cloud cover and average insolation, lightning, high winds, hail, sand storms and dust, extreme cold, extreme heat, floods, drought, fire, and SLR—and their potential impacts on electricity generation and transmission systems, fuel infrastructure and transport systems, and energy demand (Williams, 2013), the range of impacts modeled in the literature (Table 10-3) is quite limited. Most studies consider changing energy demand (specifically, changes in electricity and fuel consumption for space heating/cooling) resulting from rising temperatures as the only or primary climate change impact. These studies draw on recent literature refining the relationship between climate change and energy demand: the demand for natural gas and oil in residential and commercial sectors tends to decline with climate change because of less need for space heating, and demand for electricity tends to increase because of greater need for space cooling (Gabrielsen et al., 2005; Kirkinen et al., 2005; Mansur et al., 2005; Eskeland and Mideksa, 2010; Mideksa and Kallbekken, 2010; Rübbelke and Vögele, 2010).

Studies using a Computable General Equilibrium (CGE) model that consider only climate impacts in the energy sector find that the effect on GDP in 2050 is in the range of –0.3% to 0.03% (Bosello et al., 2007a) and –1.3% to –0.6% (Jochem et al., 2009). These findings are largely consistent despite the fact that Bosello et al. (2007a, 2009) are global studies that model only the change in demand due to rising temperatures, whereas Jochem et al. (2009) focus on the European Union (EU) and model the change in demand plus six other climate impacts.

Studies using CGE models that examine the aggregate changes in GDP brought on by climate impacts in energy and several other sectors have also primarily found similar shifts in GDP. Aaheim et al. (2009) conclude that in 2100 in cooler regions in the EU, GDP changes by –1% to –0.25% and in warmer regions changes by –3% to –0.5%. Boyd and Ibarraran (2009) project a –3% change in GDP in 2026 for Mexico, consistent with the warmer regions modeled by Aaheim et al. (2009). Roughly consistent with each other, Aaheim et al. (2009) and Eboli et al. (2010) find GDP impacts for the predominantly cooler regions of Japan, the EU, Eastern Europe and the Former Soviet Union (EEFSU), and Rest of Annex I as having a "significant positive impact," while the predominantly warmer regions of the USA, EEx (China/India, Middle East/Most of Africa/Mexico/parts of Latin America), and the Rest of the World have a "significantly negative impact." Jorgenson et al. (2004) find that overall GDP impacts are –0.6% to 0.7% in 2050 for the USA, which stands in contrast to Eboli et al. (2010) with a "significantly negative impact" in the USA.

Several CGE studies attempt to evaluate how adaptation changes in the energy sector impact GDP but do not examine specific adaptation options since CGE models lack the necessary technological detail. They make general assumptions about the effectiveness of adaptation policy in reducing climate impacts. Jorgenson et al. (2004) find that pessimistic assumptions about adaptation imply a 0.6% reduction in GDP in 2050 but optimistic assumptions lead to a 0.7% gain in GDP. Aaheim et al. (2009) conclude that adaptation can mitigate the costs of climate change by 80% to 85%, and Boyd and Ibarraran (2009) find that adaptation can shift a 3% GDP loss in 2026 in Mexico to a gain in GDP of 0.33%.

Partial equilibrium models, by their nature, do not have a full macroeconomic representation and therefore rarely report changes in GDP. Instead, these models focus on details in the energy sector, such as price and quantity effects for fuels and electricity (and the mix of generation). For example, Rübbelke and Vögele (2013) conclude that the short-term effects of climate-related problems affecting water cooling and hydropower production can have negative distributional effects. de Lucena et al. (2010) find that rising temperature and changing precipitation lead to the need for an additional 153 to 162 TWh per year by 2035 with a capital investment of US$48 to 51 billion.

Golombek et al. (2011) report a 1% increase in the price of electricity for Western Europe in 2030 stemming from rising temperatures that affect demand and thermal efficiency of supply, as well as water inflow. UNDP (2011) finds between a 0.06% and 1.74% increase in electricity system costs for Macedonia resulting from temperature changes. Gabrielsen et al. (2005) conclude that for Nordic countries in 2040, as a result of rising temperatures that affect demand, changes in water inflow, and changes in wind speeds, the wholesale price of electricity will decline by 10%. Koch et al. (2012) conclude that thermal plant outages in Berlin resulting from heat wave-driven water temperatures that exceed regulatory limits can amount to a cumulative cost of about US$80 million over the period 2010 through 2050 for 2850 MW of capacity. Assuming an 80% capacity factor, the premium for high water temperatures in Berlin is US$0.1 per MWh. The magnitude of change in electricity price is small in each of the previously mentioned studies that evaluate gradual temperature increases.

In contrast, studies that consider shorter-term heat waves and water shortages find considerably higher price impacts. Bye et al. (2008) consider a hypothetical water shortage scenario—25% lower inflow over 2 years—in Nordic countries and conclude that the price of electricity can double over a 2-year period and then return to normal as water flow returns. McDermott and Nilsen (2013) find more generally that electricity prices in Germany increase by 1% for every degree that water temperatures rise above 25°C and by 1% for every 1% that river levels fall. DOE (2009) also finds that a drought scenario can lead to average monthly electricity prices that are 8.1% (November) to 24.1% (July) higher. Pechan and Eisenack (2013) find that an equivalent of the 2006 German heat wave can result in an increase in electricity prices of 11% or even 24% (affected plants running at minimum output) and 50% (affected plants at zero output).

10.2.5. Summary

The balance of evidence emerging from the literature assessed in this section suggests that climate change per se will likely increase the demand for energy in most regions of the world. At the same time, increasing temperature will decrease the thermal efficiency of fossil, nuclear, biomass, and solar power generation technologies (Mideksa and Kallbekken, 2010). However, gradual temperature-induced impacts on energy supply will probably make a relatively small contribution to the cost of energy and electricity. Acute heat waves and droughts can have a much greater, albeit short-term, impact on electricity prices. In addition, many other potential climate impacts on energy supply are possible but have not been fully studied, leading to cost estimates to date, based only on temperature change, that underestimate the full cost of climate change on energy supply. Preexisting subsidies may distort signals for adaptation. Climate change impacts on energy supply will be part of an evolving picture dominated by technological development in the pursuit for safer, less expensive, and more reliable energy sources and technologies as well as mitigation and adaptation response pathways.

Given the limitations in the literature, sweeping conclusions about results may be premature on macroeconomic implications. However, some narrow conclusions are possible. The change in GDP due to temperature-induced changes in energy demand—even if combined with other climate impacts—range from –3% to 1.2%. Jochem et al. (2009) provide the most detailed and comprehensive study, and report only a 1.3% drop in GDP in 2050 in Europe due to at least seven climate impacts in the energy sector. The GDP impact in warmer regions tends to be greater than in cooler regions, which benefit from less need for space cooling. Energy-related economic impact is anticipated to be negative for developing countries and positive in developed countries. Adaptation within the energy sector can lower the cost of climate change, but these results may be driven largely by assumption because specific policies have not been modeled in these macroeconomic impact studies. Results from some of the partial equilibrium models suggests that CGE modeling studies, which largely focus on changes in energy demand, may be neglecting some potentially costly impacts from extreme weather events such as drought (see, e.g., Box CC-WE), which, if modeled, may lead to greater GDP losses than reported thus far in the literature.

Much research is still needed to understand the implications of climate change and extreme weather on the energy sector and to identify cost-effective adaptation options. The best understood area is the implications of climate on energy demand. A comprehensive evaluation of a full range of supply-side climate change impacts and adaptation options for all aspects of energy infrastructure is needed. This information will lead to an improved assessment of climate impacts due to the use of better, empirically based assumptions about the relationship of climate impacts and the economy, as well as about the effectiveness of adaptation options.

10.3. Water Services

This section focuses on economic aspects of climate change in water-intensive sectors and infrastructure to provide water services. The climate change impacts on biophysical water system, including the engineering aspects of water infrastructure, are assessed in Chapter 3. There is a limited set of studies published in this area and conclusions are limited by the scope of information to date.

10.3.1. Water Infrastructure and Economy-Wide Impacts

Between the 1950s and the 1990s, the annual economic losses from large extreme events, including floods and droughts, increased 10-fold, with developing countries being hardest hit (Kabat et al., 2003). Over the past few decades, flood damage constitutes about a third of the economic losses inflicted by natural hazards worldwide (Munich Re, 2005). The economic losses associated with floods worldwide have increased by a factor of five between the periods 1950–1980 and 1996–2005 (Kron and Berz, 2007). In 1990–1996 alone, there were six major floods throughout the world in which the number of fatalities exceeded 1000, and 22 floods with losses exceeding US$1 billion each (Kabat et al., 2003). Although these increases are primarily due to several non-climatic drivers, climatic factors are also partly responsible (Kundzewicz et al., 2007). Chapter 4 of the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) provides a comprehensive look at the impacts of extreme events on water supply (IPCC, 2012) and flooding at a wide range of spatial scales.

Most of the studies examining the economic impacts of climate change on the water sector have been carried out at the local, national, or river-basin scale; and the global distribution of such studies is skewed toward developed countries (Schreider et al., 2000; Chen et al., 2001; Middelkoop et al., 2001; Choi and Fisher, 2003; Hall et al., 2005; Hurd and Rouhi-Rad, 2013). In other studies, the economic impacts of climate variability on floods and droughts in developing countries were reported as substantial. These studies address climate variability; climate change may impact both mean and variability of the hydro-climatic system. The floods associated with the 1997–1998 El Niño and the drought associated with the 1998–2000 La Niña show a cost to Kenya of 11% and 16% of GDP, respectively (Mogaka et al., 2006). Floods and droughts are estimated to cost Kenya about 2.4% of GDP annually at mid-century, and water resources degradation a further 0.5% (Mogaka et al., 2006). For Ethiopia, economy-wide models incorporating hydrological variability show a drop in projected GDP growth by up to 38% compared to when hydrological variability is not included (World Bank, 2006). Syria is projected to experience reduction in economy-wide growth and incomes of urban households (Breisinger et al., 2013). However, it is not hydrological variability per se that causes the problem, but rather a lack of the necessary capacity, infrastructure, and institutions to mitigate the impacts (Grey and Sadoff, 2007). Similarly, future flood damages will depend not only on changes in the climate regime, but also on settlement patterns, land use decisions, flood forecasting quality, warning and response systems, and other adaptive measures (Pielke and Downton, 2000; Changnon, 2005; Ward et al., 2008). In many developing countries, water-related impacts are likely to be more pronounced with climate change (Chapter 3) and associated economic costs can be expected to be more substantial in the future, holding all other factors constant.

Climate change could increase the annual cost of flooding in the UK almost 15-fold by the 2080s under high emission scenarios. If climate change increased European flood losses by a similar magnitude, annual costs could increase by up to US$120 to 150 billion, for the same high emission scenarios (ABI, 2005). Feyen et al. (2012) project average annual damage in the EU to increase to US$18 to 28 billion by 2100 depending on the scenario, compared to US$8.5 billion today. Continental U.S. mean annual flood damages may increase by US$5 billion and US$12 billion in 2050 and 2100, respectively (Wobus et al., 2013). Ntelekos et al. (2010) estimate a range of US$7 to 19 billion, depending on the economic growth rate and the emissions scenarios. Dasgupta et al. (2010) report that by 2050 Bangladesh will face incremental cost to flood protection (against both sea and river floods) of US$2.6 billion initial costs and US$54 million annual recurring costs. Ward et al. (2008) found that the average annual costs to adapt to a 1-in-50-year river flood to range from US$3.5 to 6.0 billion per year for low- to upper-middle-income countries over the period 2010–2050 for the SRES A2 scenario.

10.3.2. Municipal and Industrial Water Supply

Municipal and industrial water supply economic systems are also impacted through changes in precipitation patterns and quantities. These impacts are evaluated as current costs of building in resiliency to the system to adapt to anticipated future changes. For example, the costs of adaptation to maintain supply and quality of water for municipal and industrial uses have been reported for the Assabet River near Boston (Kirshen et al., 2006), Toronto (Dore and Burton, 2001), and Quito (Vergara et al., 2007). Initial analysis indicates that adaptation measures may be beneficial for water infrastructure with an economic and engineering life of more than 25 years. Nassopoulos et al. (2012) suggest that neglecting to account for future climate change while designing water supply reservoirs can cost 0.2 to 2.8% of the net present value, based on analysis for Greece. For sub-Saharan Africa, adapting urban water infrastructure (storage facilities, wastewater, and additional supply infrastructure) to a 30% reduction in runoff could be US$2 to 5 billion per year (Muller, 2007). Climate change impacts on the Berg River in South Africa are estimated to account for 20% revenue loss for the water supply provider and 15.2% loss in social welfare (Callaway et al., 2012). For the Organisation for Economic Co-operation and Development (OECD), the cost of adaption in the water supply sector is 1 to 2% of base costs and would save US$6 to 12 billion per year (Hughes et al., 2010). U.S. impacts are estimated to be less than 1% of municipal and industrial welfare (Hurd et al., 2004; Strzepek et al., 2013). In Colorado, a 30% decrease in annual runoff will result in a 12% treatment cost increase and a 22% rise in residential costs (Towler et al., 2011).

Ward et al. (2010) estimate the costs of adaptation to climate change to ensure enough raw water to meet future industrial and municipal water demand for each country to 2050. Increased demand is assumed to be met through a combination of increased reservoir yield and alternative backstop measures. The global adaptation costs are estimated to be US$12 billion per year (0.04 to 0.06% of GDP), on top of US$73 billion per year to meet the needs of development, with 83 to 90% in developing countries. The highest costs are in sub-Saharan Africa, and may be as high as 16% of the global total. Adding adaptive measures to water infrastructure adds 10 to 20% to the total costs of developing countries meeting the water-related millennium goals (Ward et al., 2010).

10.3.3. Wastewater and Urban Stormwater

More frequent heavy rainfall events may overload the capacity of sewer systems and water and wastewater treatment plants more often, and increased occurrences of low flows will lead to higher pollutant concentrations. It is projected for USA in 2100 that national wastewater treatment costs will increase by US$0.6 to 8 billion per year (Henderson et al., 2013). The annual costs of urban stormwater system adaptation, averaged costs over 17 climate models simulating the SRES A2 emissions scenario, is US$3 billion per year in low- to upper-middle-income nations over the period 2010–2050 (Hughes et al., 2010). Adaptation costs estimates (for a 10-year, 24-hour storm in 2100) for various locations in the USA are relatively low; for example, US$135 million for Los Angeles, US$7 million for Boston, and US$40 million for Chicago (Neumann et al., 2013). Adapting bridges to altered urban floods could cost US$140 to 250 billion in the USA through the 21st century (Wright et al., 2012).

10.3.4. Inland Navigation

See Section 10.4.4.

10.3.5. Irrigation

Climate change impacts on the economics of irrigation reflect the anticipated change in temperature, precipitation, and agricultural demand and practices. Assessments of surface, ground, and gray water irrigation supplies are addressed in Chapter 3; implications for food production are covered in Chapter 7. By 2080, the global annual costs of additional irrigation water withdrawals for currently existing irrigated land are estimated at US$24 to 27 billion (Fischer et al., 2007). The global cost of improved irrigation efficiency to maintain yields is US$1.5 to 2.0 billion per year for the A2 scenario in developing countries in 2050 (Nelson et al., 2009).

Adaptation to maintain agricultural production in Ethiopia would be best achieved by better soil water management with the application of integrated irrigation and drainage systems, improved irrigation efficiency, and research related to on-farm practices; adaptation costs range from US$68 million per year for the dry scenario dominated by irrigation, to US$71 million per year under the wet scenario dominated by drainage (Strzepek et al., 2010).

10.3.6. Nature Conservation

Climate change is expected to worsen many forms of water pollution, including the load of sediments, nutrients, dissolved organic carbon, pathogens, pesticides, and salt, as well as thermal pollution, increased precipitation intensity, and low flow periods (Kundzewicz et al., 2007). Future water demands for nature conservation will be different than today's (see Chapter 4). There is no published assessment of the economic implications.

10.3.7. Recreation and Tourism

Tourism and recreation use substantial amounts of water but the implications of climate change-induced changes in tourism and recreation on water demand have yet to be quantified. See Section 10.6.

10.3.8. Water Management and Allocation

Water scarcity and competition for water, driven by institutional, economic, or social factors, may mean that water assumed to be available for a sector is not and thus economic analyses at the sectoral level are crucial; inter-sectoral and economy-wide assessments are needed for comprehensive economic impacts of water services.

Changes in water availability, demand, and quality due to climate change would impact water management and allocation decisions. Traditionally, water managers and users have relied on historical experience when planning water supplies and distribution (Adger et al., 2007; UNFCCC, 2007). Under a changing climate, existing allocations may no longer be appropriate. Arndt et al. (2012) examine the implications of alternative development paths and water allocations to suggest climate-smart development strategies in Africa; under stress situations, allocations of water to energy-generation and irrigation may have economy-wide welfare implications. Water resource-related climate change impacts on the U.S. economy measured as cumulative undiscounted welfare changes over the 21st century range from plus US$3 trillion for wet scenarios to minus US$13 trillion under dry scenarios (in US$^{2000}; Henderson et al., 2013).

10.3.9. Summary

Globally, greenhouse gas-induced increases in flooding and droughts may have substantial economic impacts (capital destruction, sectoral disruption) while estimates of adaptation costs (construction, defensive investment) range from relatively modest to relative high levels (see Box CC-WE).

10.4. Transport

The impact of climate change and sea level rise on transport has received qualitative, but limited quantitative, focus in the published literature. The impact depends greatly on the climatic zone the infrastructure is in and how climate change will be manifest. There are three major zones:

Geographic Zone	*Changes in Climate Expected to Impact Vulnerability*
Freezing/Frost Zone	Permafrost, freeze-thaw cycles, precipitation, flooding, SLR, and storms (coastal)
Temperate Zone	Precipitation intensity, flooding, maximum daily precipitation, SLR, and storms (coastal)
Tropical Zone	Precipitation intensity, flooding, maximum daily precipitation, SLR, and storms (coastal)

As detailed in Sections 10.4.1, 10.4.2, 10.4.4, and 10.4.5, several studies have explored the potential impacts of climate change on the transport sector—focusing, for example, on safety or disruptions of service. Quantitative, economic analyses of the impact on physical infrastructure include Larsen et al. (2008), Chinowsky et al. (2010, 2011), and Hunt and Watkiss (2010) and on wider economic implications, Arndt et al. (2012).

Adaptation options for each sub-sector of transport infrastructure have been studied. Existing literature includes CCSP (2008) and Chinowsky et al. (2011), with proposed strategies ranging from technical to political, including focus on upgraded design specifications during new construction, retrofitting structures, and modified land use planning in coastal areas. Adaptation and resiliency to extreme events is of particular interest as they may have a cascading impact, in that the loss of critical infrastructure assets will negatively affect the recovery and resiliency of a community (Kirshen et al., 2008a,b).

10.4.1. Roads

Studies on the direct effects of climate change on road networks are focused primarily on qualitative predictions and surveys concerning impacts on road durability (National Research Council, 2008; Koetse and Rietveld, 2009; Eisenack et al., 2012; Ryley and Chapman, 2012); with some studies of the quantitative effects (Nemry and Demirel, 2012; Chinowsky et al., 2013). Noted impacts from changes in precipitation and temperature include changes in required road maintenance. These quantitative studies focus on specific impacts such as maintenance in an effort to quantify the long-term costs that need to be assumed by national and regional road agencies. Examples of the metrics used include kilometers of roads lost over time, redistribution requirements of transport funds, and benefits from adaptation on long-term maintenance.

Chapter 8 addresses the indirect effects of climate change on roads in the areas of congestion and safety. As an example, increases in heavy precipitation events will negatively affect driving safety through decreased driver visibility and changing surface conditions (Qiu and Nixon, 2008).

Paved road degradation is directly related to heat stress that can lead to softening of the pavement as temperatures exceed design thresholds (Lavin, 2003), and an increase in the number of freeze-thaw cycles impacts both the base and pavement surface (FHWA, 2006). The melting of permafrost in northern climates, as well as increased precipitation and flooding, threaten the integrity of road base and sub-bases (Qin et al., 2005). Drainage presents a specific problem for urban areas that experience rainfall above their built capacity and will influence new design standards and costs for urban transport (City of Chicago, 2008; Hunt and Watkiss, 2010; Lemmen and Warren, 2010). Increased fire danger from droughts could also pose a threat to roads.

Unpaved roads are vulnerable to a number of climate-based factors especially to increasingly intense precipitation, leading to wash out and disruption of service (Chinowsky and Arndt, 2012). Increased precipitation in agricultural areas may have negative economic impacts in addition to the direct impact on infrastructure. In cold climates, temporary winter roads are susceptible to warming and associated lower connectivity of rural areas and reduced economic activity in northern climates (Mills and Andrey, 2002). Warming could imply that ice roads can no longer be maintained.

Bridges form a core component of any nation's infrastructure. However, highway bridges that cross water, ubiquitous to most highway networks, are exposed to climate changes via flood events and associated changes in long-term flow regimes. The potential disruptions that could occur due to the loss of or damage to these bridges are numerous. Estimates in the USA range from US$140 to 250 billion to address adaptation requirements for bridge infrastructure over the next 50 years (Wright et al., 2012). Similarly, European estimates range from US$350 to 500 million per year to adapt bridge infrastructure (Nemry and Demirel, 2012). Once again, the potential cascading effects of these failures will affect the economic conditions of multiple sectors.

10.4.2. Rail

Rail beds are susceptible to increases in precipitation, flooding and subsidence, SLR, extreme events, and incidence of freeze-thaw cycles (Nemry and Demirel, 2012). In northern climates, the melting of permafrost (URS, 2010) may lead to ground settlement, undermining stability (Larsen et al., 2008). Increased temperatures pose a threat to rail through thermal expansion. In urban areas, increased temperatures pose a threat to underground transport systems that will see a burden on increased need for cooling systems (Hunt and Watkiss, 2010). For example, US$290 million has been allocated to finding a workable solution for increasing the capacity of London's underground cooling system (Arkell and Darch, 2006). The complexity of addressing rail infrastructure is increased through differences in design specifications, multiple types of rail and materials used, and uncertainty about the changes in future temperatures.

10.4.3. Pipeline

Increases in precipitation and temperature affect pipelines through scouring of base areas and unearthing of buried pipelines (URS, 2010), compromised stability of bases built on permafrost, and increases in necessary maintenance (National Research Council, 2008; URS, 2010). Temperature increase can result in thermal expansion of the pipelines, causing cracking at material connection points. In tropical areas, increased precipitation may lead to landslides that can compromise pipeline infrastructure (Sweeney et al., 2005). There has been no economic assessment of the impacts.

10.4.4. Shipping

Impacts on inland navigation vary widely due to projected rise or fall in water levels. Overall, the effects on inland navigation are projected to be negative, and are region specific.

Increased frequency of flood periods will stop ship traffic on the Rhine more often; longer periods of low flow will also increase the average annual number of days during which inland navigation is hampered or stagnates due to limited load carrying capacity of the river; channel improvements can only partly alleviate these problems (Middelkoop et al., 2001). Economic impact could be substantial given the value of navigation on the Rhine (Krekt et al., 2011). See Chapter 23.

Virtually all scenarios of future climate change project reduced Great Lakes water levels and connecting channel flows, mainly because of increased evaporation resulting from higher temperatures. The potential economic impact may result in reductions in vessel cargo capacities and increases in shipping costs. The lower water levels predicted as a result of a doubling of atmospheric CO_2 could increase annual transportation costs by 29%, while more moderate climate change could result in a 13% increase in annual shipping costs. The impacts vary across commodities and routes (Millerd, 2010).

Warming leads to increased ice-free navigation and a longer shipping season, but also to lower water levels from reduced runoff (Lemmen and Warren, 2010). In cold regions, increased days of ice-free navigation and a longer shipping season could impact shipping and reduce transportation costs (National Research Council, 2008; Koetse and Rietveld, 2009; UNCTAD, 2009; UNECE and UNCTAD, 2010), although movement in ice waters such as the Canada Arctic sea could become more difficult (Wilson et al., 2004; Stewart et al., 2007).

Ports will be affected by climate changes including higher temperatures, SLR, increasingly severe storms, and increased precipitation (Becker et al., 2011; Nursey-Bray and Miller, 2012). However, (the need to prioritize) adaptation of ports has been overshadowed by a focus on potential impacts. Training of port personnel is needed to begin the adaptation process. More than US$3 trillion in port infrastructure assets in 136 of the world's largest port cities are vulnerable to weather events (CCSP, 2008; UNCTAD, 2009; UNECE and UNCTAD, 2010).

Increased storminess in certain routes may raise cost of shipping through additional safety measures or longer routes that are less storm prone (UNCTAD, 2009; UNECE and UNCTAD, 2010). Transport costs would increase or new routes sought if storms disrupt supply chains by destroying port infrastructure connecting road or rail (Becker et al., 2011). Increased storminess may also affect passage through lock systems (CCSP, 2008; UNCTAD, 2009). Increased storminess may increase maintenance costs for ships and ports and result in more frequent weather-related delays.

10.4.5. Air

Hotter air is less dense. In summer months, especially at airports located at high altitudes, this may result in limitations for freight capacity, safety issues, and weather-related delays, unless runways are lengthened (National Research Council, 2008; Pejovic et al., 2009). Chapman (2007) suggests that technological innovations will negate the challenges posed by extreme temperatures.

Increased storminess at airports, particularly those located in coastal regions, may increase the number of weather-related delays and cancellations (Pejovic et al., 2009; Lemmen and Warren, 2010) and increase maintenance and repair costs (Gusmao, 2010). Clear-air turbulence will increase in the Atlantic corridor, leading to longer and bumpier trips (Williams and Joshi, 2013). The impact of climate change on airport pavement is very similar to paved roads (DOT, 2002; Allard et al., 2007). The effect of temperature and increased precipitation intensity on airports imposes a risk to the entire facility if pavements are not adapted to these increases (Pejovic et al., 2009).

10.5. Other Primary and Secondary Economic Activities

This section assesses the impact of climate change on primary (agriculture, mining) and secondary economic activities (manufacturing, construction), unless they are discussed elsewhere in the chapter or the report.

10.5.1. Primary Economic Activities

Primary economic activities (e.g., agriculture, forestry, fishing, mining) are particularly sensitive to the consequences of climate change because of their immediate dependence on the natural environment. In some regions, these activities dominate the economy.

10.5.1.1. Crop and Animal Production

Chapters 7 and 9 assess the impact of climate change on agriculture, including the effects on (international) markets for crops.

10.5.1.2. Forestry and Logging

Chapter 4 assesses the biophysical impact of climate change on forestry. Including adaptation in forest management, climate change will accelerate tree growth. This will reduce prices to the benefit of consumers everywhere. Low to mid latitude producers will benefit too as they switch to short-rotation forest plantations. Mid- to high-latitude producers will be hurt by lower prices while their productivity increases only modestly (Sohngen and Mendelsohn, 1997, 1998; Sohngen et al., 2001; Perez-Garcia et al., 2002; Lee and Lyon, 2004; Seppala et al., 2009). The value of the forest land in Europe would fall between 14 and 50% by 2100 (Hanewinkel et al., 2013). Different trees will be affected differently (Aaheim et al., 2011a,b). Higher biomass prices differentially impact different forest-based industries (Moiseyev et al., 2011).

10.5.1.3. Fisheries and Aquaculture

Chapter 4 assesses impacts of climate change on freshwater ecosystems, and Chapters 5, 6, and 30 on marine ecosystems. These assessments include the effects on commercially valuable fish stocks, but exclude the effects on markets. Adaptation and markets will substantially change the effect of climate change on fisheries (Link and Tol, 2009; Yazdi and Fashandi, 2010).

Allison et al. (2009), using an indicator-based approach, analyzed the vulnerability of capture fishery of 132 economies. Incongruously, they find that the sign and size of climate-driven change for particular fish stocks and fisheries are uncertain but are expected to lead to either increased economic hardship or missed opportunities for development in countries that depend on fisheries but lack the capacity to adapt. A major part of the gross turnover of nine key fish and cephalopod species in the Bay of Biscay remains potentially unaffected by climate change (Le Floc'h et al., 2008). In contrast, Iberian-Atlantic sardine biomass and profitability declines due to climate change (Garza-Gil et al., 2011). The economic impact of climate change on fisheries is dominated by the impact of management regime and market (Eide and Heen, 2002; McGoodwin, 2007; Eide, 2008; McIlgorm, 2010; Merino et al., 2010).

Ocean acidification has a range of impacts on the biological systems (Doney et al., 2009), but the studies on the economic impacts of ocean acidification are rare (Cooley and Doney, 2009; Hilmi et al., 2013). Using a partial equilibrium model, Narita et al. (2012) estimate the economic impact of ocean acidification on shellfish. By the turn of this century the aggregate cost could be greater than US$100 billion.

10.5.1.4. Mining and Quarrying

Climate change will affect exploration, extraction, production, and shipping in the mining and quarrying industry (Pearce et al., 2011). An increase in climate-related hazards (such as forest fires, flooding, windstorm) affects the viability of mining operations and potentially increases operating, transportation, and decommissioning costs.

Most infrastructure was built based on presumption of a stable climate, and is thus not adapted to climate change (Ford et al., 2010, 2011; Pearce et al., 2011). Damigos (2012) estimates the damages due to climate change under the SRES A1B scenario for the period 2021–2050 of the extent of US$0.8 billion for the Mediterranean Region. Note that other factors such as research and development might influence the viability of mining operations by lowering the cost of adaptation.

10.5.2. Secondary Economic Activities

10.5.2.1. Manufacturing

Climate change will impact manufacturing through three channels. First, climate change affects primary economic activities (see Section 10.5.1), and this means that prices and qualities of inputs are different. Second, the supply chain is affected, or the quality of the product. The impact of climate change on energy demand is well understood (see Section 10.2). Using a biophysical model of the human body, Kjellstrom et al. (2009) project labor productivity to fall, particularly of manual labor in humid climates. Labor productivity losses will be accentuated by increased incidences of malaria and vector-borne diseases. Note that the loss in labor productivity can be offset by the technological progress. Hübler et al. (2008) uphold the finding with a German case study, and Hsiang (2010) corroborates it with a statistical analysis of weather data and labor productivity in the Caribbean for 1970–2006. Some manufacturing activity is location specific, perhaps because it is tied to an input or product market, and will thus have to cope with the current and future climate; other manufacturing has discretion over its location (and hence its climate). Third, climate change affects the demand for products. This is pronounced for manufactures that supply primary sectors (Kingwell and Farré, 2009) and construction material (see Section 10.5.2.2). Unfortunately, there are only a few studies that quantify these effects (see Section SM10.1 of the on-line supplementary material).

10.5.2.2. Construction and Housing

Climate and climate change affect construction in three ways. First, weather conditions are one of the key factors in construction delays and thus costs. Climate change will change the length of the building season. In addition, precipitation affects the cost of construction through temporary flood protection (coffer) structures, slope stabilization management, and dewatering of foundations. There are adaptation measures that may reduce some of the costs. Apipattanavis et al. (2010) show a reduction in the expected value of road construction delays and associated costs. Second, buildings and building materials are designed and selected to withstand a particular range of weather conditions. As climate changes, design standards will change too. Exterior building components including windows, roofing, and siding are all specified according to narrow environmental constraints. Climate change will introduce conditions that are outside the prescribed operating environment for many materials, resulting in increased failures of window seals, increased leaks in roofing materials, and reduced lifespan of timber or glass-based cladding materials. Similarly, the interior building systems that allow for proper airflow in a facility face significant issues with climate change. For example, the increases in temperature and precipitation will lead to increased humidity as well as indoor temperatures. This requires increased airflow in facilities such as hospitals, schools, and office buildings—that is, upgrades to air conditioning and fan units, and perhaps further renovations that may be significant in scope and cost. Third, a change in the pattern of natural disasters will imply a change in the demand for rebuilding and repair. Unfortunately, these impacts have yet to be quantified (Hertin et al., 2003). Note that the direction and magnitude of the effect on construction and housing costs will possibly vary geographically. Cost impacts due to changing precipitation and storms patterns (magnitude, frequency, and/or variation) will vary as these changes are expected to vary by region as well. Air to air heat exchangers, heat recovery ventilators, and dehumidifiers and other technologies may be useful in adapting indoor air quality.

10.6. Recreation and Tourism

Recreation and tourism is one of the largest sectors of the world economy. In 2011, it accounted for 9% of global expenditure, and employed 260 million people (WTTC, 2011). Supply of tourism services is the dominant activity in many regional economies.

Recreation and tourism encompass many activities, some of which are more sensitive to weather and climate than others: compare sunbathing to angling, gambling, business seminars, family visits, and pilgrimage. Climate change would affect the place, time, and nature of these activities.

There is a large literature on the impact of climate change on tourism (Gössling et al., 2012; Scott et al., 2012a; Pang et al., 2013). Some studies focus on the changes in the behavior of tourists—that is, the demand for recreation and tourism services (see Section 10.6.1). Other studies look at the implications for tourist operators and destinations—that is, the supply of recreation and tourism services (see Section 10.6.2). A few studies consider the interactions between changes in supply and demand (see Section 10.6.3).

10.6.1. Recreation and Tourism Demand

Conventionally, recreation does not involve an overnight stay whereas tourism does. That implies that recreation, unlike tourism, is done close to home. Whereas tourists, to a degree, chose the climate of their holidays, recreationists do not (although climate is a consideration in the choice where to live). Tourists would adapt to climate change by changing the region, timing, and activities of their holidays; recreationists would adapt only timing and activities (Becken and Hay, 2007).

10.6.1.1. Recreation

There has been no research on systematic differences of recreational behavior due to differences in climate at large spatial scales. The impact of climate change on recreation is therefore largely unknown. The economic impact is probably limited, as people will tend to change the composition rather than the level of their time and money spent on recreation. For instance, Shaw and Loomis (2008) argue that climate change would increase boating, golfing, and beach recreation at the expense of skiing.

There are case studies that indicate the impact of climate change on recreation. Buckley and Foushee (2012) find a trend toward earlier visits to U.S. national parks between 1979 and 2008. They argue this is due to climate change, but do not rigorously test this hypothesis nor control for other explanations. Whitehead et al. (2009) find a substantial decrease in the recreational value of sea shore fishing in North Carolina due to

SLR. Daugherty et al. (2011) conclude that climate change will make it more difficult to guarantee adequate water levels for boating and angling in artificial reservoirs. Pouta et al. (2009) project a reduction in cross-country skiing in Finland, particularly among women, the lower classes, and urban dwellers. Shih et al. (2009) find that weather affects the demand for ski lift trips. Hamilton et al. (2007) highlight the importance of "backyard snow" to induce potential skiers to visit ski slopes. One could expect people to adopt other ways of enjoying themselves but such alternatives were excluded from these studies.

There are positive effects too (Richardson and Loomis, 2005). Scott and Jones (2006, 2007) foresee an increase in golf in Canada due to climate change. Kulshreshtha (2011) sees positive impacts on recreation on the Canadian Prairies, and Coombes et al. (2009) predict an increase in beach tourism in East Anglia. Graff Zivin and Neidell (2010) find that people recreate indoors when the weather is inclement.

Scott et al. (2007) estimate the relationship between visitors to Waterton Lakes National Park and weather variables for 8 years of monthly observations, and use this to project an increase in visitor numbers due to climate change. A survey among current visitors indicates that a deterioration of the quality of nature would reduce visitor numbers. Jones et al. (2006) study the impact of climate change on three festivals in Ottawa. They argue for heat wave preparedness for Canada Day, find that skating on natural ice may become impossible for Winterlude, and that the dates of the Tulip Festival may need to be shifted to reflect changing phenology.

10.6.1.2. Tourism

Climate (Becken and Hay, 2007; WTO and UNEP, 2008) and weather (Álvarez-Díaz and Rosselló-Nadal, 2010; Rosselló-Nadal et al., 2010; Rossello, 2011; Førland et al., 2012; Day et al., 2013; Falk, 2013) are important factors in tourist destination choice, and the tourist sector is susceptible to extreme weather (Forster et al., 2012; Hamzah et al., 2012; Tsai et al., 2012). Eijgelaar et al. (2010), for instance, argue that so-called "last chance tourism" is a strong pull for tourists to visit Antarctica to admire the glaciers while they still can. Farbotko (2010) and Prideaux and Mcnamara (2012) use a similar mechanism to explain the rise in popularity of Tuvalu as a destination choice. Huebner (2012) find no impact of future climate change on current travel choices. Taylor and Ortiz (2009) show that domestic tourists in the UK often respond to past weather; the hot summer of 2003 had a positive impact on revenues of the tourist sector. Denstadli et al. (2011) find that tourists in the Arctic do not object to the weather in the Arctic; Gössling et al. (2006) reaches the same conclusion for tourists on Zanzibar; and Moreno (2010) for tourists in the Mediterranean.

There are a number of biometeorological studies of the impact of climate change on tourism. Yu et al. (2009a) find that Alaska has become more attractive over the last 50 years and Florida less attractive to tourists. Yu et al. (2009b) conclude that the climate for sightseeing has improved in Alaska, while the climate for skiing has deteriorated. Matzarakis et al. (2010) construct a composite index of temperature, humidity, wind speed, and cloud cover, and use this to map tourism potential. Lin and Matzarakis (2008, 2011) apply the index to Taiwan POC and eastern China. Endler and Matzarakis (2010a,b, 2011) use an index to study the Black Forest in Germany in detail, highlighting the differences between summer and winter tourism, and between high and low altitudes (Endler et al., 2010). Zaninović and Matzarakis (2009) and Matzarakis and Endler (2010) use this method to study Freiburg and Hvar. Matzarakis et al. (2007) project this potential into the future, finding that the Mediterranean will probably become less attractive to tourists. Hein et al. (2009), Perch-Nielsen et al. (2009), Giannakopoulos et al. (2011), Amelung and Moreno (2012), and Amengual et al. (2012) reach the same conclusion, but also point out that Mediterranean tourism may shift from summer to the other seasons. Giannakopoulos et al. (2011) note that coastal areas in Greece may be affected more than inland areas because, although temperature would be lower, humidity would be higher. Moreno and Amelung (2009), on the other hand, conclude that climate change will not have a major impact (before 2050) on beach tourism in the Mediterranean because sunbathers like it hot (Moreno, 2010; Rutty and Scott, 2010). Amelung et al. (2007) use a weather index for a global study of the impact of climate change on tourism, finding shifts from equator to pole, summer to spring and autumn, and low to high altitudes. Perch-Nielsen (2010) combines a meteorological indicator of exposure with indicators of sensitivity and adaptive capacity, and uses this to rank the vulnerability of beach tourism in 51 countries. India stands out as the most vulnerable, and Cyprus as the least vulnerable.

The main criticism of most biometeorological studies is that the predicted gradients and changes in tourism attractiveness have rarely been tested to observations of tourist behavior. De Freitas et al. (2008) validate their proposed meteorological index to survey data. Moreno et al. (2008) and Ibarra (2011) use beach occupancy to test meteorological indices for beach tourism. Gómez-Martín (2006) tests meteorological indices against visitor numbers and occupancy rates. All four studies find that weather and climate affects tourists, but in a different way than typically assumed by biometeorologists.

Maddison (2001) estimates a statistical model of the holiday destinations of British tourists, Lise and Tol (2002) for Dutch tourists, Bujosa and Rosselló (2012) for Spanish tourists in Spain, and Bigano et al. (2006) for international tourists from 45 countries. These models control for as many other variables as possible; their focus on the average tourist may be misleading, and their representation of climate may be oversimplified (Gössling and Hall, 2006). Tourists have a clear preference for the climate that is currently found in southern France, northern Italy, and northern Spain. People from hot climates care more about the climate in which they spend their holidays than people from cool climates. Whereas (Bigano et al., 2006) find regularity in *revealed* preferences, Scott et al. (2008b) find pronounced differences in *stated* preferences between types of people.

Bigano et al. (2007) and Hamilton et al. (2005a,b) construct a simulation model of domestic and international tourism and climate change (but not SLR), considering the simultaneous change in the attractiveness of all potential holiday destinations (Dawson and Scott, 2013); Hamilton and Tol (2007) downscale these national results to the regions of selected countries. Two main findings emerge. First, climate change would drive tourists to higher latitudes and altitudes. International tourist arrivals would fall, relative to the scenario without warming, in hotter countries, and rise in colder countries. Tourists from northwestern Europe, the main origin worldwide of international travelers at present, would be more inclined to spend the holiday in their home country, so that the total number of international tourists falls. Second, the impact of climate change is dominated by the impact of population growth and, particularly, economic growth. In the worst affected countries, climate change slows down, but nowhere reverses, growth in the tourism sector.

10.6.2. Recreation and Tourism Supply

Studies on the supply side often focus on ski tourism. Warming is expected to raise the altitude of snow-reliable ski resorts, and fewer resorts will be snow reliable (Dawson et al., 2009; Hendrikx et al., 2012, 2013; Steger et al., 2012). Snowmobiling will be negatively affected too (Mcboyle et al., 2007; Scott et al., 2008a). Artificial snow-making cannot fully offset the loss in natural snowfall (Elsasser and Bürki, 2002; Scott et al., 2006; Hoffmann et al., 2009), particularly in lower areas (Wolfsegger et al., 2008; Morrison and Pickering, 2012; Schmidt et al., 2012), and water scarcity and the costs of snowmaking will be increasingly large problems (Scott et al., 2003, 2007; Steiger and Mayer, 2008; Hendrikx and Hreinsson, 2012; Matzarakis et al., 2012; Pons-Pons et al., 2012); skiers prefer natural over artificial snow (Pickering et al., 2010). Tourism alternatives to skiing or non-tourism alternatives need to be considered as a source of economic development (Bicknell and Mcmanus, 2006; Moen and Fredman, 2007; Scott and McBoyle, 2007; Tervo, 2008; Bourdeau, 2009; Potocka and Zajadacz, 2009; Hill et al., 2010; Pickering and Buckley, 2010; Steiger, 2010; Serquet and Rebetez, 2011; Landauer et al., 2012; Matzarakis et al., 2012). Other socioeconomic trends dominate the impact of climate change (Hopkins et al., 2012; Steiger, 2012).

Other studies consider beach tourism. Scott et al. (2012b) highlight the vulnerability of coastal tourism facilities to SLR. Hamilton (2007) finds that tourists are averse to artificial coastlines, so that hard protection measures against SLR would reduce the attractiveness of an area. Raymond and Brown (2011) survey tourists on the Southern Fleurieu Peninsula. They conclude that tourists who are there for relaxation worry about climate change, particularly SLR, while tourists who are there to enjoy nature (inland) do not share that concern. Becken (2005) finds that tourist operators have adapted to weather events, and argues that this helps them to adapt to climate change. Belle and Bramwell (2005) find that tourist operators on Barbados are averse to public adaptation policies. Uyarra et al. (2005) find that tourists on Barbados would consider holidaying elsewhere if there is severe beach erosion. Buzinde et al. (2010a,b) find that there is a discrepancy between the marketing of destinations as pristine and the observations of tourists, at least for Mexican beach resorts subject to erosion. They conclude that tourists have a mixed response to environmental change, contrary to the officials' view that tourists respond negatively. Jopp et al. (2013) find that an increase in tourism in the shoulder season may offset losses in the peak season in Victoria.

Some studies focus on nature tourism. Cavan et al. (2006) find that climate change may have a negative effect on the visitor economy of the Scottish uplands as natural beauty deteriorates through increased wild fires. Saarinen and Tervo (2006) interviewed nature-based tourism operators in Finland, and found that about half of them do not believe that climate change is real, and that few have considered adaptation options. Nyaupane and Chhetri (2009) argue that climate change would increase weather hazards in the Himalayas and that this would endanger tourists. Uyarra et al. (2005) find that tourists on Bonaire would not return if coral were bleached. Hall (2006) finds that small tourist operators in New Zealand do not give high priority to climate change, unless they were personally affected by extreme weather in recent times. The interviewed operators generally think that adaptation is a sufficient response to climate change for the tourism sector. Klint et al. (2012) find that tourist operators in Vanuatu give low priority to adaptation to climate change and Jiang et al. (2012) find Fiji poorly prepared. Saarinen et al. (2012) find that tourist operators in Botswana think that climate change would not affect them. Wang et al. (2010) note that glacier tourism is particularly vulnerable to climate change, highlighting the Baishiu Glacier in China. Brander et al. (2012) estimate the economic impacts of ocean acidification on coral reefs under four IPCC marker scenarios using value transfer function approach and find that the annual economic impacts increase rapidly overtime, though it remains a small fraction of total income.

While the case studies reviewed above provide rich detail, it is hard to draw overarching conclusions. A few studies consider all aspects of the impact of climate change for particular countries or regions (Ren Guoyu, 1996; Harrison et al., 1999). In France, the Riviera may benefit because it is slightly cooler than the competing coastal resorts in Italy and Spain; the Atlantic Coast, although warming, would not become more attractive because of increased rainfall; it is not probable that the increase in summer tourism in the mountains would offset the decrease in winter tourism (Ceron and Dubois, 2005). In the Great Lakes regions, there is a reduced tourism potential in winter but increased opportunities in summer (Dawson and Scott, 2010). Tourist operators in Australia find the uncertainty about climate change too large for early investment in adaptation (Turton et al., 2010).

10.6.3. Market Impacts

There are only two papers that consider the economic impacts of rather stylized climate change-induced changes in tourism supply and demand. Both studies use a global computable general equilibrium model, assessing the effects on the tourism sector as well as all other markets. Berrittella et al. (2006) consider the consumption pattern of tourists and their destination choice. They find that the economic impact is qualitatively the same as the impact on tourist flows (discussed above): Colder countries benefit from an expanded tourism sector, and warmer countries lose. They also find a drop in global welfare, because of the redistribution of tourism supply from warmer (and poorer) to colder (and richer) countries.

Bigano et al. (2008) extend the analysis with the implications of sea level rise. The impact on tourism is limited because coastal facilities used by tourists typically are sufficiently valuable to be protected against SLR. The economic impacts on the tourism sector are reinforced by the economic impacts on the coastal zone; the welfare losses due to the impact of climate change on tourism are larger than the welfare losses due to SLR.

10.7. Insurance and Financial Services

10.7.1. Main Results of the Fourth Assessment Report and IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation on Insurance

More intense or frequent weather-related disaster would affect property insurance, of which coverage is expanding with economic growth (WGII AR4 Section 7.4.2.2.4). Insurability can be preserved through risk-reducing measures. Adaptation to climate change can be incentivized through risk-commensurate insurance premiums. Improved risk management would further financial resilience (WGII AR4 Sections 7.4.2.2.4, 7.6.3). Insurance is linked to disaster risk reduction and climate change adaptation, because it enables recovery, reduces vulnerability, and provides knowledge and incentives for reducing risk (IPCC, 2012).

10.7.2. Fundamentals of Insurance Covering Weather Hazards

Insurance is organized either through private markets, publicly, or public-private partnerships. It internalizes catastrophe risk costs prior to catastrophic events, reducing the economic impact of weather-related and other disasters to individuals, enterprises, and governments—thus stabilizing income and consumption, and decreasing societal vulnerability (Melecky and Raddatz, 2011; see also Section 17.5.1). Insurance is based on the law of large numbers: the larger the portfolio of uncorrelated and relatively small risks, the more accurately the average loss per policy can be predicted and charged accordingly, allowing for a lower premium than with a smaller ensemble. Besides spreading risk over a diversified insured population, insurance spreads risk over time. However, weather-related disasters such as floods simultaneously affect many, and thus violate the principle of uncorrelated risks. Consequently, large losses are much more probable, the loss variance is greater, and the tail risk is higher (Kousky and Cooke, 2012).

If insurance coverage is to be maintained, insurers would need more risk-based capital to indemnify catastrophic losses and remain financially solvent. This coverage is purchased in the reinsurance and capital markets. The capital costs account for a substantial portion of premiums and the affordability and viability of weather insurance are subjects of ongoing research given future climate change (Charpentier, 2008; Clarke and Grenham, 2012; Maynard and Ranger, 2012).

Increasing volatility and burden of losses in many regions are expected to fundamentally impact the industry, leading insurers to adapt their business to the changing risk (Herweijer et al., 2009; Phelan et al., 2011; Mills, 2012; Paudel, 2012). However, prevailing short-term contracts facilitate adaptation to changing circumstances (Botzen et al., 2010a).

10.7.3. Observed and Projected Insured Losses from Weather Hazards

Direct and insured losses from weather-related disasters have increased substantially in recent decades, both globally and regionally (Bouwer et al., 2007; Crompton and McAneney, 2008; IPCC, 2012; Munich Re, 2013; Smith and Katz, 2013; Swiss Re, 2013c). Global insured weather-related losses in the period 1980–2008 increased by US$[2008]1.4 billion per year on average (Barthel and Neumayer, 2012). As a rule, insured loss figures are more accurate than direct economic loss estimates, because insurance payouts are closely monitored. Often they are the basis for estimates of direct overall losses (Kron et al., 2012; Smith and Katz, 2013). Economic growth, including greater concentrations of people and wealth in periled areas and rising insurance penetration, is the most important driver of increasing losses.

Growth-induced changes in past losses are removed by normalizing to current levels of destructible wealth. So far, only one study analyzes normalized global weather-related insured losses (Barthel and Neumayer, 2012), but the period is too short (1990–2008) to support a meaningful analysis of trends. A few studies focus on specific perils and regions, in particular Australia, USA, and Europe. Trends were detected for the USA and Germany, but not for Australia and Spain (Table 10-4). Such trends can be influenced by changing damage sensitivities, adaptive measures, different normalization, and changes in insurance—besides changing hazards (Crompton and McAneney, 2008; Bouwer, 2011; Barthel and Neumayer, 2012; IPCC, 2012). Prevention measures such as flood control structures or improved building standards would offset an increase in hazard (Kunreuther et al., 2009, 2012). Given such confounding factors, it can be challenging to estimate to what degree developments in losses convey a climate signal (IPCC, 2012; Kron, 2012). Nonetheless, normalized direct natural disaster losses have already been demonstrated to properly

Frequently Asked Questions

FAQ 10.2 | How does climate change impact insurance and financial services?

Insurance buys financial security against, among other perils, weather hazards. Climate change, including changed weather variability, is anticipated to increase losses and loss variability in various regions through more frequent and/or intensive weather disasters. This will challenge insurance systems to offer coverage for premiums that are still affordable, while at the same time requiring more risk-based capital. Adequate insurance coverage will be challenging in low- and middle-income countries. Other financial service activities can be affected depending on the exposure of invested assets/loan portfolios to climate change. This exposure includes not only physical damage but also regulatory/reputational effects, liability, and litigation risks.

reflect climate variability on various time scales (Pielke and Landsea, 1999; Welker and Faust, 2013).

Studies analyzing changes in climate variables and insured losses in parallel are still rare. Variability and mean level of thunderstorm-related insured losses in the USA in the period 1970–2009 have substantially increased, while meteorological thunderstorm forcing has risen in parallel (Sander et al., 2013). The number of days that a regional insurer in southwest Germany sustains hail losses displays an upward trend since 1986, while meteorological severe storm indicators also show upward trends (Kunz et al., 2009). Although more studies find increases of large hail in Europe, general data and monitoring issues hindered assessing more than *low confidence* in observed meteorological trends (WGI AR5 Section 2.6.2.4). Corti et al. (2009) found an increase in modeled and partly observed insured subsidence losses in France over the period 1961–2002, consistent with a *likely* increase in dryness in Mediterranean regions (WGI AR5 Section 2.6.2.3). The observed rise in U.S. normalized insured flood losses (Barthel and Neumayer, 2012) may partly correspond to *very likely* increased heavy precipitation events in central North America (WGI AR5 Section 2.6.2.1), while the evidence for climate-driven changes in river floods is not compelling (WGI AR5 Section 2.6.2.2). Declining anthropogenic aerosol emissions may partly explain the recent upswing in hurricane hazard and losses (WGI AR5 Sections 2.6.3, 14.6; Table 10-4). Apart from detection, loss trends have not been conclusively attributed to anthropogenic climate change; most such discussions are not based on scientific attribution methods.

Many GCM-based projection studies agree that extreme winter storm wind speeds fall in the Mediterranean and increase in west, central, and northern Europe (WGI AR5 Section 14.6.2.2). Loss ratios—that is, insured loss divided by insured value—follow the same pattern (Schwierz et al., 2010; Donat et al., 2011; Pinto et al., 2012; see also Table 10-5). Return periods per loss level are projected to shorten in large parts of Europe, indicating more frequent high losses (Pinto et al., 2012; see Table 10-5). Projected overall losses and fatalities develop accordingly (Narita et al., 2010; IPCC, 2012). Across three modeling approaches calibrated to

Table 10-4 | Observed normalized insured losses from weather hazards (trends significant at the 10% level are indicated as a trend).

Region	Peril accounted for in normalized insured property losses	Observation period	Trend in insured losses—otherwise specified (aggregation mode)	Reference
World	All weather-related	1990–2008	No trend (annual aggregates)	1
Australia	Aggregate of bushfire, flood, hailstorm, thunderstorm, tropical cyclone	1967–2006	No trend (annual aggregates)	7
West Germany	All weather-related	1980–2008	Positive trend (annual aggregates)	1
	Winter storms			
	Floods	1980–2008	No trend (annual aggregates)	
	Convective events			
Southwest Germany	Hailstorm	1986–2004	Positive trends in annual frequency of days exceeding thresholds of daily damage claim counts Increase in annual count of hail damage claims	8
Spain	Floods	1971–2008	No trend (annual aggregates)	2
USA east of 109°W	Convective events (hail, heavy precipitation and flash flood, straight-line wind, tornado)	1970–2009 (March to September)	Standard deviation (variability) by a factor 1.65 greater for 1990–2009 than for 1970–1989 Mean annual loss by a factor 2.67 greater for 1990–2009 than for 1970–1989 Data: normalized insured loss exceeding US$150 million per event, annual aggregates	9
USA	Winter storms (ice storms, blizzards and snow storms)	1949–2003	Positive trend (pentade totals) Positive trend (average loss per state, pentade totals)	3
	All flood ("flood only" and floods specifically caused by convective storms, tropical cyclones, snow melt)	1972–2006	Positive trend (annual aggregates)	4
	Tropical cyclones	1949–2004	Increase (7-year totals) No statistical trend assessment.	5
	Hailstorm	1951–2006	Focus on top-ten major hailstorm losses of the period 1951–2006. Increase in frequency and loss in the 1992–2006 period as compared to 1951–1991. No statistical trend assessment	6
	All weather-related	1973–2008	Positive trend (annual aggregates)	1
	Floods			
	Convective events			
	Winter storms			
	Tropical cyclones			
	Heat episodes			
	Cold spells	1973–2008	No trend (annual aggregates)	

Sources: [1]Barthel and Neumayer (2012); [2]Barredo et al. (2012); [3]Changnon (2007); [4]Changnon (2008); [5]Changnon (2009a); [6]Changnon (2009b); [7]Crompton and McAneney (2008); [8]Kunz et al. (2009); [9]Sander et al. (2013).

Table 10-5 | Climate change projections of insured losses and/or insurance prices.

Hazard	Insurance line	Region	Projected changes in future time slices relative to current climate (spatial distribution and vulnerability of insured values assumed to be unchanged over time)
Winter storm	Homeowners' insurance	Europe	Projected increases in mean annual loss ratio lie in a range from one- to two-digit percentages in time slices before and around 2050 for regions such as France, Belgium/Netherlands, UK/Ireland, Germany, and Poland, with larger increases at the end of the century. Southern European regions expect decreases, such as Portugal/Spain (SRES A1B, A2).[4,5,8,13–15,19] Currently rare and high annual loss ratios are projected to occur more often: today's 20-year, 10-year, and 5-year return periods appear strongly reduced by the end of the century for individual countries. For entire Europe they will roughly be halved (SRES A2).[16] Accordingly, return periods will have higher loss levels associated,[10,19] e.g., the 25-year loss in Germany is expected to rise by 5–41% in 2041–2070 (SRES A1B).[8,10]
River flood, maritime flood, flash flood from rainfall, melting snow	Property and business interruption insurances	Europe, North America	Germany: projected increases in mean annual insured flood loss according to a seven-member dynamical downscaling ensemble mean (SRES B1, A1B, A2) are 84% (2011–2040), 91% (2041–2070), and 114% (2071–2100).[7] United Kingdom: projected increases in mean annual insured flood loss are 8% (for a +2°C rise in global mean temperature) and 14% (for a +4°C rise), with the one-in-hundred-year loss higher by 18% and 30%, respectively.[4] Norway, Canada: losses from heavy precipitation in property and business interruption insurances in three city areas in Canada are projected to rise by 13% (2016–2035), 20% (2046–2065), and 30% (2081–2100) in a five-member ensemble mean (IS92a, SRES A2/B2, A2)[3]. In three counties across southern Norway precipitation and snow melt insurance losses are expected to be higher by approximately 10–21% (SRES A2) and 17–32% (SRES B2) at the end of the century.[9] The Netherlands: expected annual property loss caused by increasing river discharge and sea level with an assumed flood insurance system is projected to lie by 125% higher in 2040 relative to 2015 (corresponding to 24 cm sea level rise) and by 1784% higher in 2100 (85 cm sea level rise).[1]
Tropical cyclone	Foremost property insurance lines	North America, Asia	USA: three of four GCMs driving a specific tropical cyclone and loss model entail increasing insured hurricane losses over time (SRES A1B).[6] Two GCM outputs at coarser resolution for the end of the century produce contradictory results of prolonged (ECHAM5/MPIOM A2) versus shortened (MRI/JMA A1B) return periods of current loss levels.[17] Analogously, a wide range of model projections is reflected in price levels of Florida's hurricane wind insurance that are projected to change by –20% to +5% (2020s) and –28% to +10% (2040s) (under the assumptions of strained reinsurance capacity, i.e., hard market conditions, and current adaptation).[12,18] These approaches demonstrate uncertainty in the sign of change. China: projected increases of insured typhoon losses are 20% (for a +2°C rise in global mean temperature) and 32% (for a +4°C scenario), with the one-in-hundred-year loss higher by 7% and 9%, respectively.[4]
Hailstorm	Homeowners' insurance, agricultural insurances	Europe	The Netherlands: losses from outdoor farming insurance and greenhouse horticulture insurance are projected to increase by 25–29% and 116–134%, respectively, for a +1°C rise in global mean temperature. For a +2°C scenario, projected increases will be higher at 49% to 58% and 219% to 269%, respectively (statistical model).[2] Germany: projected increases in mean annual loss ratios from homeowners' insurance due to hail are 15% (2011–2040) and 47% (2041–2070) (SRES A1B, statistical model).[8]
Storms, pests, diseases	Paddy rice insurance	Asia	Japan: paddy rice insurance payouts are projected to decrease by 13% by the 2070s, on the basis of changes in standard yield and yield loss (A2).[11]

Notes: GCM = General Circulation Model; ECHAM5 = European Centre for Medium Range Weather Forecasts and (Max Planck Institute of Meteorology) Hamburg, fifth GCM generation; MRI = Meteorological Research Institute of Japan Meteorological Agency (JMA); SRES = Special Report on Emission Scenarios.

Sources: [1]Aerts and Botzen (2011); [2]Botzen et al. (2010b); [3]Cheng et al. (2012); [4]Dailey et al. (2009); [5]Donat et al. (2011); [6]Emanuel (2011); [7]German Insurance Association (Gesamtverband der Deutschen Versicherungswirtschaft) (2011); [8]Gerstengarbe et al. (2013); [9]Haug et al. (2011); [10]Held et al. (2013); [11]Iizumi et al. (2008); [12]Kunreuther et al. (2012); [13]Leckebusch et al. (2007); [14]Pinto et al. (2007); [15]Pinto et al. (2009); [16]Pinto et al. (2012); [17]Raible et al. (2012); [18]Ranger and Niehoerster (2012); [19]Schwierz et al. (2010).

German insurance data, the 25-year loss is projected (SRES A1B) to change by –10% to +26% (2011–2040), +5% to +41% (2041–2070), and +45% to +58% (2071–2100) against 1971–2000, keeping exposures and damage sensitivities constant (Held et al., 2013). Although it is *unlikely* that the North Atlantic response to climate change is just a simple poleward shift of the storm track, overall confidence in the magnitude of regional storm track changes is low (WGI AR5 Section 14.6.3).

Direct losses and fatalities from flooding will increase with climate change in various locations in the absence of adequate adaptation, given *very likely* widespread increases in heavy precipitation (WGI AR5 Sections 11.3.2.5.2, 12.4.5.4; see also IPCC, 2012). This is selectively reflected in studies projecting mean annual insured heavy rainfall and flood losses to rise with climate change in the UK, the Netherlands, Germany, southern Norway, and the Canadian province of Ontario (Table 10-5).

Direct losses and fatalities from tropical cyclones will increase with exposure and may increase with the frequency of very intense cyclones in some basins (WGI AR5 Section 14.6; Nordhaus, 2010; IPCC, 2012; Peduzzi et al., 2012). Ranger and Niehoerster (2012), Kunreuther et al. (2012), and Raible et al. (2012) found insured hurricane losses change in opposite directions across a range of dynamical and statistical model projections, whereas a high-resolution approach tends to support a long-term increase (Emanuel, 2011). Here, increased probabilities of upward shifted accumulated loss might be detectable by 2025 at earliest, whereas a significant loss trend might emerge much later (Crompton et al., 2011; Emanuel, 2011).

Insured typhoon-related property losses in China are projected to increase (Dailey et al., 2009). Averaged across four GCMs, Mendelsohn et al. (2012) project rising direct losses for Central America, the Caribbean, North America, and East Asia. Narita et al. (2009) report an increase in damages and fatalities in all parts of the world.

Hailstorm insurance losses in the Netherlands (Botzen et al., 2010b) and Germany (Gerstengarbe et al., 2013) are projected to increase, consistent with more severe thunderstorms (WGI AR5 Section 12.4.5.5). Paddy rice insurance payouts in Japan are projected to decrease (Iizumi et al., 2008; see Table 10-5).

Rising insured wealth will increase both losses and premium income, not necessarily altering the ratio of both. Such automatic compensation is not effective for changing hazards. Hence, projected ratios of losses to premiums or sums insured (while assuming constant insured property) are an approximation of the climate change impact (Donat et al., 2011). Additional impact factors such as future economic growth (Aerts and Botzen, 2011) or changing vulnerability are rarely projected.

10.7.4. Fundamental Supply-Side Challenges and Sensitivities

10.7.4.1. High-Income Countries

The provision of weather hazard insurance is contingent on an insurer's ability to find a balance between affordability of the premiums and costs that have to be covered by the revenue. Costs include the expected level of losses, expenses for risk assessment, product development, marketing, operating, and claims processing. Moreover, the revenue must provide a return on shareholders' equity and allow for the purchase of external capital to cover large losses (Charpentier, 2008; Kunreuther et al., 2009).

The balance between affordability and profitability is sensitive to climate change. Increases in large weather-related losses may corrode an insurer's solvency if it fails to adjust its risk management, or is hampered in doing so by price regulation (Grace and Klein, 2009). In addition, misguided incentives for development in hazard-prone areas, as with the U.S. National Flood Insurance Program (Michel-Kerjan, 2010; Kousky and Kunreuther, 2010; GAO, 2011) can aggravate the situation (see Table 10-6).

The additional uncertainty induced by climate change translates into a need for more risk capital (Charpentier, 2008; Grace and Klein, 2009; Kunreuther et al., 2009). This raises insurance premiums and affects the economy (Table 10-6). Health and life insurance may also be affected through the health impacts of climate change (Hecht, 2008). Liability insurance, too, may be susceptible to climate change. So far, no damages have been awarded for greenhouse gas emissions as such, but litigation where damages are sought is pending (Heintz et al., 2009; Mills, 2009; Patton, 2011). Defense cost coverage under liability insurance in such cases depends on the specific contractual wording (Supreme Court of Virginia, USA, 2012; see Table 10-6).

10.7.4.2. Middle- and Low-Income Countries

Middle- and low-income countries account for a small share of worldwide non-life insurance: approximately 14% of premiums in 2012 (Swiss Re, 2013b). In high-income countries, some 37% of direct natural disaster losses have been covered by insurance in the period 1980–2011, about 4% in middle-income countries, and even less in low-income countries (Wirtz et al., 2013). For instance, only about 1% of direct overall losses in the 2010 floods in Pakistan were insured (Munich Re., 2011).

Table 10-6 | Fundamental supply-side challenges and sensitivities.

Challenges that might increase in the climate change context	Example/explanation
Failure to reflect temporal changes in hazard condition in risk management	After the devastating 2004 and 2005 hurricane seasons, the losses of Florida's homeowners' insurance accumulated since 1985 exceeded the cumulative direct premiums earned by 31%. Consequences of the upswing and peak in hurricane activity: one insurer liquidated, two seized by regulation due to insolvency; reduced coverage availability in high-risk areas.[9]
Misguided incentives additionally increasing risk	US National Flood Insurance Program (NFIP) allows for a vicious circle of built-up areas already existing within flood plains pressing authorities to construct or improve protecting levees that in turn lead to even more development attracted by NFIP premium discounts, although exposed to extreme flooding events.[11,22] In addition, the large majority of older properties situated within flood plains and accounting for 16% of losses in the period 1978–2008 pay premiums substantially below the risk-adequate level.[14; see also 1,6,7,11,15] In this respect, premium incentives to reduce residual flood risk have been missing. Policyholders residing in flood plains where flood cover was made precondition for mortgage drop the cover after only 2–4 years, accounting for missing insurance penetration and insufficient build-up of NFIP risk capital.[11,14,15] All these features, among others, account for the fact that NFIP has continuously been running a cumulative operating deficit, reaching more than US$20 billion in 2006, after the big hurricanes.[14]
Non-quantifiable uncertainties increasing risk	There is ambiguity as to what degree climate change may modify regional weather hazards—model projections are not unequivocal,[2,3] and there is uncertainty about prospects of post-disaster regulatory/jurisdictional pressures, e.g., to extend claims payments beyond the original coverage.[9] Such uncertainties materialize in risk-based capital loadings.[12]
Liability insurance impacted by new climate risk	Chances of success for claims based on CO_2 emissions in the USA seem small, owing to legal obstacles,[4,5,8,18] even though allocation schemes to overcome these hurdles are being discussed.[17,20] Defense costs could be covered by liability insurance.[20] CO_2 emissions were declared pollution (US Supreme Court/EPA). Existing and future regulation on limits for CO_2 emissions could continue to displace liability claims for CO_2 emissions and at the same time create new liability risks in case of non-compliance. These risks have not yet been adequately taken into account, somewhat similar to the early stages of environmental liability claims in the USA in the 20th century.[10,16] The Supreme Court of Virginia ruled in 2012 that coverage under liability insurance for claims based on CO_2 emissions and defense costs depends on the specific occurrence-definition underlying the contract (e.g., if the cover pertains to accident, warming due to CO_2 emissions and resulting damage does not match this definition).[19]
Share of insurance in national risk financing	In the years following weather-related disasters countries with high insurance penetration show almost no impact on sovereign deficit and increasing economic output (GDP), whereas low-penetration countries experience substantially rising government deficit and missing positive change in output.[13,21] The absence of developed insurance systems, as is the case in many middle- and low-income countries, translates into greater macroeconomic vulnerability than with developed insurance systems.

Sources: [1]Burby (2006); [2]Charpentier (2008); [3]Collier et al. (2009); [4]Ebert (2010); [5]Faure and Peeters (2011); [6]GAO (2010); [7]GAO (2011); [8]Gerrard (2007); [9]Grace and Klein (2009); [10]Hecht (2008); [11]Kousky and Kunreuther (2010); [12]Kunreuther et al. (2009); [13]Melecky and Raddatz (2011); [14]Michel-Kerjan (2010); [15]Michel-Kerjan and Kunreuther (2011); [16]Mills (2009); [17]Patton (2011); [18]Stewart and Willard (2010); [19]Supreme Court of Virginia USA (2012); [20]Taylor and Tollin (2009); [21]von Peter et al. (2012); [22]Zahran et al. (2009).

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The small share of insurance in risk financing in middle- and low-income countries may be insufficient because other options, such as external credit or donor assistance, can be unreliable and late. This leaves a financial gap in the months immediately following an EWE, often exacerbated by overstretched public finances. Pre-disaster financing instruments such as insurance or trigger-based risk-transfer products have proven to be effective means of providing prompt liquidity for households, businesses, and governments (Ghesquiere and Mahul, 2007; Linnerooth-Bayer et al., 2011; Melecky and Raddatz, 2011; IPCC, 2012; von Peter et al., 2012; see Table 10-6). These may become more important if disaster incidence increases with climate change (Collier et al., 2009; Hochrainer et al., 2010; IPCC, 2012).

It is challenging to increase catastrophe insurance coverage because of low business volumes, high transaction costs, and high reinsurance premiums following large disasters. Small-scale insurance schemes in middle- and low-income countries may find it difficult to obtain sufficient risk capital (Cummins and Mahul, 2009; Mahul and Stutley, 2010).

Microinsurance schemes, keeping transaction costs at the lowest operable level, mainly provide health and life insurance to households and small enterprises in low-income markets. Supply of property insurance suffers from correlated weather risks, although weather-related agricultural damages are covered. Such weather coverage is growing, typically with government and non-governmental organization (NGO) assistance or cross-subsidies from local insurers (Linnerooth-Bayer et al., 2011; Qureshi and Reinhard, 2011). These schemes may be particularly sensitive to a rise in disaster risk due to climate change (Collier et al., 2009; Leblois and Quirion, 2011; Clarke and Grenham, 2012).

Adverse selection is another challenge: clients do not always disclose their true risk, for example, a floodplain site, to the insurer so as to benefit from lower rates. Lower-risk participants may be charged too high premiums and leave the scheme, thus increasing overall risk; and in low-income countries, where data to establish homogeneous risk groups are not available, this can cause disaster insurance markets to fail. Moral hazard is another issue, where the insured adopt more risky behavior than anticipated by the insurer, particularly in the absence of proper monitoring (Barnett et al., 2008; Mahul and Stutley, 2010).

10.7.5. Products and Systems Responding to Changes in Weather Risks

10.7.5.1. High-Income Countries

A rise in weather-related disaster risk may drive the need for more risk-based capital to cover the losses. There are several options that sustain insurability. Reducing vulnerability often makes sense even if expected climate change impacts will not materialize. Theoretically, risk-based premiums incentivize policyholders to reduce their vulnerability (Hecht, 2008; Kunreuther et al., 2009; IPCC, 2012; see Table 10-7). Premium discounts for loss prevention can further promote this (Ward et al., 2008; Kunreuther et al., 2009; see Table 10-7). Moral hazard can be reduced by involving the policyholder in the payment of losses, for example, via deductibles or upper limits of insurance coverage (Botzen and van den Bergh, 2009; Botzen et al., 2009). Coordinated efforts of insurers and governments on damage prevention decrease risk (Ward et al., 2008; Reinhold et al., 2012). For example, new building standards in Florida reduced mean damage per house by 42% in the period 1996–2004 relative to pre-1996; risks can be further reduced, and premium discounts contingent on building standard are offered (Kunreuther et al., 2009, 2012). However, risk-based premiums required to incentivize vulnerability reduction are often hampered (see also Sections 15.4.4, 17.5.1). Price regulation, subsidies, competitive pressures, and bundling of perils in one product (implying cross-subsidies) have fostered underpricing. Also, availability of sufficient on-site risk information limits price adequacy, for example, for flood insurance (Maynard and Ranger, 2012).

Most commercial risk-assessment models only incipiently factor in changes in weather hazards, mainly to reflect higher hurricane frequencies (Seo and Mahul, 2009), assuming unchanging conditions for other weather hazards. Ignoring changing hazard conditions results in biased estimates of expected loss, loss variability, and risk capital requirements (Charpentier, 2008; Herweijer et al., 2009; see also Section 10.7.3). Other confounding factors, for example, systemic economic impact, in recent large losses have been addressed (Muir-Wood and Grossi, 2008; see Table 10-7). Geospatial risk-assessment tools, such as flood-recurrence zoning with premium differentiation, counteract adverse selection (Kunreuther et al., 2009; Mahul and Stutley, 2010). Some insurers have offered weather alert systems to clients (Niesing, 2004). Further, credit rating agencies and Solvency II insurance regulations in Europe contribute to enhanced disaster resilience (Michel-Kerjan and Morlaye, 2008; Grace and Klein, 2009; Kunreuther et al., 2009). Finally, insurers and researchers have projected climate change-driven losses to allow for adaptation of the industry (Section 10.7.3).

Reinsurers are key to the supply of disaster risk capital. They operate globally to diversify the regional risks of hurricanes and other disasters. Access to reinsurance enhances risk diversification of insurers. Periodic shortages in reinsurance capacity following major disasters have moderated over the last 2 decades because of easier new capital inflow (Cummins and Mahul, 2009).

Global diversification potential of large losses has fallen over recent decades because of increasing dependence between major insurance markets. For instance, the floods in Thailand in 2011 disrupted industrial hubs and global supply chains (Courbage et al., 2012). This process may continue with climate change (Sherement and Lucas, 2009; Kousky and Cooke, 2012). However, global diversification potential can be increased by developing insurance markets in middle- and low-income countries (Cummins and Mahul, 2009).

Very large loss events, say in excess of US$100 billion, may make additional capacity desirable. These disasters can be diversified in the financial securitization market (IPCC, 2012). Natural catastrophe risks do not correlate with capital market risks and hence are attractive to institutional investors. For instance, a catastrophe bond assures the investor above-market returns as long as a parametric index (e.g., wind-based) does not exceed a threshold, but pays the insurer's loss otherwise. The catastrophe bond market reached critical mass after the hurricanes of 2004 and 2005, with some US$11 billion of risk capital in effect by June 2011 (Michel-Kerjan and Morlaye, 2008; Cummins and Weiss, 2009; see Table 10-7).

Table 10-7 | Products and systems responding to changes in weather risks.

Response option	Example/explanation
Risk-adjusted premiums convey the risk to the insured, encouraging them to pursue adaptive measures.	Flood hazard insurance zoning systems, e.g., HORA (Austria), SIGRA (Italy), and ZÜRS (Germany), hamper development in high-risk zones by allocating adequately high premiums.[26] Prior to Germany's disastrous River Elbe flood in 2002, 48.5% of insured households had obtained information on flood mitigation or were involved in emergency networks and 28.5% implemented one of several mitigation measures compared with 33.9% and 20.5%, respectively, of uninsured households.[42] However, perceptions that motivate flood insurance uptake range from risk awareness[9] to pure peer group expectation[32]—the latter might blur the role of the risk-premiums-nexus in some societal contexts.
Conditions of insurance policies incentivizing vulnerability reduction	Premium discounts for compliance with local building codes or other prevention options[27,45]; share of the insured in claims payment by deductibles or upper coverage limits, and exclusion of systematically affected property[1,7,8,10,11,15,21]; long-term natural-hazard insurance tied to the property and linked to mortgages and loans granted for prevention measures.[27,28,36] The latter is contested by modeled high-risk capital requirements and ambiguity loadings, rendering multi-year policies relatively expensive and less flexible for the insurance market.[34]
Amplifying factors in large disaster losses included in risk models	Evacuation and systemic economic catastrophe impacts, adversely affecting regional workforce and repair capacity, or knock-on catastrophes following initial catastrophes, e.g., long-term flooding following hurricane landfall.[38]
Diversifying large disaster risk across securitization markets	Following the hurricane disasters of 2004 and 2005, securitization instruments, e.g., catastrophe bonds, industry loss warranties, and sidecars, acquired greater prominence, and have been recovering again from the market break in 2008.[16,18,20] Investors in insurance linked securities are attracted by the lack of correlation to typical financial market risks (e.g., currency risks) and the well defined loss-per-index structure. The higher transparency relative to other asset-backed securities, such as mortgage-backed securities, contributed to the better performance of catastrophe bonds following the financial crisis of 2007/2008.[16,18] As bonds typically cover large losses, the basis risk, i.e., suffering damage without parametric triggering, is reduced[44]; further reduction may be feasible by optimizing index measurements.[16] Weather derivatives are further instruments used to transfer risks to the capital markets.[17,27,37] Also, multiple-trigger "hybrid" products are available, combining a parametric trigger-based catastrophe bond with a trigger-based protection against a simultaneous drop in stock market prices, thereby hedging against a double hit from direct disaster loss and losses incurred by the asset management side.[5,18]
Index-based weather crop insurance products	Agricultural insurances predominantly cover crops, but also livestock, forestry, aquaculture, and greenhouses. Main products are indemnity-based crop insurance (covers for single perils and multiple-peril events), and index-based crop insurance.[41] The latter is available in 40% of middle-income countries, with enlarged systems beyond pilot implementation in India and Mexico, and growth in China.[23,33,40,46] Risk-based price signals may better foster adaptation if schemes are coupled with access to advanced technology, e.g., drought-resistant seed.[4,15,23,33] Various index definitions (cumulative rainfall, area-yield, etc.) and applications exist or have been proposed.[4,29,30,31] Adjusting to uncertain regional changes in temporal hazard condition is a basic challenge with climate change.[14,24,29]
Improvements in index-based weather insurance	Basis risk, i.e., weak correlation between index and damage, can be reduced if the index scheme is applied to an area-yield trigger in a region with homogeneous production potential (e.g., based on a sample) and/or to the uppermost disaster risk layer only.[14,15,22] It can be better absorbed if index insurance works at aggregate level, e.g., to cover crop-credit portfolios, cooperatives, or informal networks,[43] and if satellite-based remote-sensing technology can be used to establish plot identification and yield estimation and loss assessment.[22] Satellite-based forage estimation is already used for livestock index insurance in East Africa.[13] Pooling local schemes across climate regions under one cooperative parent organization, thus realizing central management, economics of scale, and risk diversification, can reduce capital requirements and advance performance.[6,12,35] The disaster risk layer and high start-up costs (weather data collection, risk modeling, education) necessitate subsidies from the state or donors.[15,33]
Sovereign insurance schemes	Economic theory about the public sector's risk neutrality argues (1) that risks borne publicly render the social cost of risk-bearing insignificant and (2) that disaster loss is seen small in comparison with a government's portfolio of diversified assets.[3] This theory proved inadequate if applied to relatively vulnerable small-sized middle- to low-income countries,[19] thereby rehabilitating sovereign insurance. For the Caribbean scheme CCRIF, which pools states, the reduction in premium cost per country is expected to be 45–50%.[31] Similar pooling schemes are being developed (e.g., African Risk Capacity, Pacific Catastrophe Risk Insurance Pilot).[2,39] Pooling natural catastrophe risks across an array of megacities has also been proposed.[25]

Sources: [1]Aakre et al. (2010); [2]Wilcox et al. (2010); [3]Arrow and Lind (1970); [4]Barnett et al. (2008); [5]Barrieu and Loubergé (2009); [6]Biener and Eling (2012); [7]Botzen and van den Bergh (2008); [8]Botzen and van den Bergh (2009); [9]Botzen and van den Bergh (2012); [10]Botzen et al. (2009); [11]Botzen et al. (2010a); [12]Candel (2007); [13]Chantarat et al. (2013); [14]Clarke and Grenham (2012); [15]Collier et al. (2009); [16]Cummins (2012); [17]Cummins and Mahul (2009); [18]Cummins and Weiss (2009); [19]Ghesquiere and Mahul (2007); [20]Guy Carpenter (2011); [21]Hecht (2008); [22]Herbold (2013b); [23]Hess and Hazell (2009); [24]Hochrainer et al. (2010); [25]Hochrainer and Mechler (2011); [26]Kron (2009); [27]Kunreuther et al. (2009); [28]Kunreuther and Michel-Kerjan (2009); [29]Leblois and Quirion (2011); [30]Leiva and Skees (2008); [31]Linnerooth-Bayer and Mechler (2009); [32]Lo (2013); [33]Mahul and Stutley (2010); [34]Maynard and Ranger (2012); [35]Meze-Hausken et al. (2009); [36]Michel-Kerjan and Kunreuther (2011); [37]Michel-Kerjan and Morlaye (2008); [38]Muir-Wood and Grossi (2008); [39]The World Bank (2013); [40]Prabhakar et al. (2013); [41]Swiss Re (2013a); [42]Thieken et al. (2006); [43]Trærup (2012); [44]Van Nostrand and Nevius (2011); [45]Ward et al. (2008); [46]Zhu (2011).

10.7.5.2. Middle- and Low-Income Countries

Index-based weather insurance is often considered well-suited to the agricultural sector in developing countries (Collier et al., 2009; IPCC, 2012). Payouts depend on a physical trigger, for example, cumulative rainfall at a nearby weather station, instead of the policyholder's condition. Thus, they can be timely; costly loss assessments and moral hazard are avoided; and adverse selection reduced (Barnett et al., 2008). Risk-based premiums can encourage adaptive responses (Mahul and Stutley, 2010; see Table 10-7). However, basis risk, where losses occur but no payout is triggered, provokes distrust. Misunderstanding and scaling up of pilots pose further difficulties (Patt et al., 2010; Leblois and Quirion, 2011; Clarke and Grenham, 2012). Suggested improvements include area-yield indices and coverage at aggregate levels to reduce basis risk, and a cooperative design (Biener and Eling, 2012; Clarke and Grenham, 2012; see Table 10-7). Application of indemnity-based insurance and index-based concepts depend on the insured's characteristics and the market setting (Herbold, 2013a; Swiss Re, 2013a). Insurance-linked services can strengthen farmers' resilience by seasonal-forecast-based agricultural guidance (AgroClima, 2013).

Improved building standards at high-risk sites in the Caribbean substantially reduce damages from tropical cyclones and increase benefits twofold over costs over a 20-year period, assuming scenarios of changing hazard inferred from past decades (Michel-Kerjan et al., 2013; Ou-Yang et al., 2013). Insurance coverage linked to credit for retrofitting could improve adaptation (Mechler et al., 2006).

Sovereign insurance is deemed appropriate in developing countries suffering from post-disaster financing gaps (see Section 10.7.4). Current schemes include government disaster reserve funds (FONDEN, Mexico) and pools of developing states' sovereign risks (e.g., CCRIF, Caribbean;

IPCC, 2012). In both cases, peak risk is transferred to reinsurance and catastrophe bonds (Table 10-7).

10.7.6. Governance, Public–Private Partnerships, and Insurance Market Regulation

10.7.6.1. High-Income Countries

Theory favors an arrangement where individual risk is insured, but the non-diversifiable component of risk (that may rise with climate change) is public (Borch, 1962; Kunreuther et al., 2009). Accordingly, many high-income states have public-private arrangements involving government intervention on peak risk (Aakre et al., 2010; Bruggeman et al., 2010; Schwarze et al., 2011; Paudel, 2012), or even public statutory insurance systems (Quinto, 2011; see Table 10-8). Expected governmental post-disaster relief has been shown to counteract insurance uptake (Raschky et al., 2013). The pro-adaptive, risk-reducing features of insurance are more effective if the price reflects the risk and the pool of insureds is larger, for example, through bundled perils (Bruggeman et al., 2010; Paudel, 2012). People who cannot afford premiums can be covered by vouchers, leaving the price signal undistorted, or by subsidies (Kunreuther et al., 2009; Aakre et al., 2010; see Table 10-8).

Insurance regulation ensures availability, affordability, and solvency, but often adopts only short- to medium-term views. Because of climate change, the role of regulators has changed to include risk-adequate pricing, risk education, and risk-reduction in the long term (Hecht, 2008; Grace and Klein, 2009; Mills, 2009).

10.7.6.2. Middle- and Low-Income Countries

A key element of risk financing is the transfer of private risks to an insurance system. This reduces the governments' burden and uncertainty due to weather disasters (Ghesquiere and Mahul, 2007; Melecky and Raddatz, 2011). Interest in public-private partnerships may evolve, for example, between government, farmers, rural banks, and insurers, in order to expedite agricultural development and resilience, for example, by means of subsidies for start-up costs and peak risk (Collier et al., 2009; Mahul and Stutley, 2010; see Table 10-8). Previously implemented systems have suffered from adverse selection and moral hazard (Makki and Somwaru, 2001; Glauber, 2004), suggesting an improved design is needed. For instance, group policies foster mutual monitoring. Programs or legislative actions that encourage purchase of insurance may increase participation rates. Further, insurance pools can diversify weather risks across larger regions, reduce premiums, and improve access to external risk capital (Mendoza, 2009; Hochrainer and Mechler, 2011; Biener and Eling, 2012; IPCC, 2012).

In least developed countries, domestic insurance markets are rare. Climate change-related disaster risk management was proposed for inclusion in the adaptation regime of the United Nations Framework Convention on Climate Change (UNFCCC). Besides prevention, insurance is a central element in these concepts, partly funded from a UNFCCC adaptation fund according to the principles of "equity and […] common but differentiated responsibilities and respective capabilities" (UNFCCC Art. 3.1; Linnerooth-Bayer et al., 2009; Warner and Spiegel, 2009; IPCC, 2012; see Table 10-8).

For insurance systems in developing markets, challenges include adequate public-private partnership framing, improved risk assessment with sufficient detail and appropriate dynamics, development of markets and regulation, and scaling-up of successful schemes. Regulatory requirements for risk-based capital, and access to reinsurance and securitization markets, further contribute to a resilient insurance system.

10.7.7. Financial Services

The financial industry apart from insurance is vulnerable to both slow-onset changes and to more frequent and/or intensive weather-related disasters. Equity investors potentially face a higher exposure than debt investors, due to exit conditions and a focus on longer-term returns in equity markets, but ultimately the impact on debt investors depends on the exposure of credit collateral to climate change (Stenek et al., 2010). In the short- to medium-term, the financial sector is better sheltered from climate change due to high capital mobility, an ability to hedge

Table 10-8 | Governance, public–private partnerships, and insurance market regulation.

Structural element	Example/explanation
Public–private arrangements involving government intervention on the non-diversifiable disaster risk portion	Systems with government intervention range from ex ante risk financing design, such as public monopoly natural hazard insurance (e.g., Switzerland, with inter-cantonal pool) or compulsory forms of coverage to maximize the pool of insureds (e.g., Spain, France, with unlimited state guarantee on top), to ex post financing design, such as taxation-based governmental relief funds (e.g., Austria, Netherlands). In between these boundaries rank predominantly private insurance markets, in several countries combined with governmental post-disaster ad hoc relief (e.g., Germany, Italy, UK, Poland, USA)[13]; see also [1,3,4,10,11,12,14].
Care for people who cannot afford insurance	Either by funds outside the insurance system, e.g., insurance vouchers, or by premium subsidies (particularly for the catastrophic risk portion).[1,6,14]
Public-private partnership to expedite agricultural development	Insurance improves the farmers' creditworthiness, which in turn strengthens their adaptive capacity. For instance, by means of loans farmers can step from low-yield to higher-yield cropping systems.[2,8,9]
Concepts for adaptation-oriented climate change risk management frameworks linked to United Nations Framework Convention on Climate Change (UNFCCC)	Risk prevention and risk reduction often are the starting points that can absorb many of the smaller weather risks, and various forms of insurance, including international coordination, are meant to cover all of the remaining risks.[7,15,16] A global framework, where the wealthy agree to pool risks with the most vulnerable, equals social insurance that is different from a risk-based share in insurance funds.[5]

Sources: [1]Aakre et al. (2010); [2]Barnett et al. (2008); [3]Botzen and van den Bergh (2008); [4]Bruggeman et al. (2010); [5]Duus-Otterström and Jagers (2011); [6]Kunreuther et al. (2009); [7]Linnerooth-Bayer et al (2009); [8]Linnerooth-Bayer et al. (2011); [9]Mahul and Stutley (2010); [10]Monti (2012); [11]Paudel (2012); [12]Schwarze and Wagner (2007); [13]Schwarze et al. (2011); [14]Van den Berg and Faure (2006); [15]Warner and Spiegel (2009); [16]Warner et al (2012).

against a range of business risks, and an aptitude for the development of new products to cater for changing demand in particular with respect to risk transfers and investment in growing markets (Oliver Wyman, 2007; Whalley and Yuan, 2009). In the longer-term, some risks associated with climate change will be more difficult to diversify in particular for financial institutions with local reach.

There are few papers on the impact of climate change on the financial sector (other than insurance). Surveys agree with earlier views (WGII AR3 Section 8.4) that climate change is perceived as a material threat by few bankers and asset managers. There is growing awareness of climate change impacts, as illustrated by increasing membership of sector initiatives—such as the Carbon Disclosure Project, the UN Principles for Responsible Investment, or the Global Reporting Initiative—potentially influencing the responsiveness of the sector to climate change (Brimble and Stewart, 2009). However, only a few financial institutions have systematically factored in climate change into their risk management and analytical framework (Cogan et al., 2008; Furrer et al., 2012).

While direct physical impact (i.e., damage to financial infrastructure) is not seen to be a material issue, this may change in the future in light of the exposure of major financial centers to rising sea levels and the reliance on complex IT infrastructure. Moreover, there is an increasing share of equity allocated to infrastructure and real estate that is more long-term oriented and could face higher maintenance and adaptation requirements (Stenek et al., 2010; Mercer, 2011).

Indirect impacts may become material over the next few decades, for example, value losses of assets/loan portfolios as a result of physical damage. Regulatory and reputational effects, together with liability and litigation risks linked to climate change are of concern too (Cogan et al., 2008; Mercer, 2011; Furrer et al., 2012). However, legitimacy concerns linked to climate change (as reflected by clients) are insufficient, overshadowed by the financial crisis, or mitigated by the size and influence of the financial sector (Brimble and Stewart, 2009).

It is difficult to quantify how significant the impact of climate change will be for the industry. While it is not probable that climate change alone will affect the liquidity or financial capacity of an institution, the financial performance of both equity and debt markets could be weakened by a variety of factors including changes in market conditions through climate-driven price variations, higher capital and operating expenditure, or aggravation of country risk but also regulatory drivers, for example, higher capital reserve requirements to cover higher on- and off-balance-sheet exposures (Stenek et al., 2010).

10.7.8. Summary

More frequent or more severe extreme weather events, and increased uncertainty about such hazards, would lead to higher insurance premiums and reduced cover in several regions, to the detriment of the insured, and perhaps to reduced profitability of insurers, and to the detriment of their shareholders. Improvements in risk management, product innovation, financial innovation, and better regulation would partially alleviate these impacts.

10.8. Services Other than Tourism and Insurance

Other service sectors of the economy include waste management, wholesale and retail trade, engineering, government, education, defense, and health. Contributions to the economy vary substantially by country; however, overall worldwide economic activity related to government accounts for approximately 30% of global expenditures.

10.8.1. Sectors Other than Health

The literature on the impact of climate change on other sectors of the economy is sparse (see Section SM10.1 of the on-line supplementary material). Few studies have evaluated the possible impacts of climate change, and particularly the economic impacts, on these sectors. Tamiotti et al. (2009) conducted a qualitative assessment of climate and trade. Travers and Payne (1998) and Subak et al. (2000) find that weather affects retail, mostly through transfers in the economy. Sabbioni et al. (2009) note that climate change may require a greater effort to protect cultural heritage. Chapter 12 discusses the impact of climate change on violent conflict, which has implications for military expenditures.

10.8.2. Health

Climate change-related alterations in weather patterns, particularly extreme weather and climate events, have the potential to affect the health sector through impacts on infrastructure and the delivery of health care services from changing demand. Increased demands for services put additional burdens on public health and health care personnel and supplies, with potential economic consequences. For example, hydrologic disasters (floods and wet mass movements) in 2011 were associated with 20% of all reported disaster deaths and 19% of total damages (Guha-Sapir et al., 2012).

Health care facilities are priority infrastructure that can be damaged by weather and climate events, compromising critical resources required for patient treatment; physical damage and destruction of equipment and buildings; and possibly requiring evacuation of critical care patients, with attendant risks for the patients (Carthey et al., 2009). Adverse impacts on transportation (such as flooded roads) can further affect access and evacuation. The ability of health care facilities to properly care for the affected and for those with ongoing health issues requiring medication or treatment may be compromised by very large events that affect multiple health care facilities. Areas projected to experience increases in extreme events could consider additional "surge capacity" to manage such events without interruption of service (Banks et al., 2007; Hess et al., 2009).

Although the proportion of individuals seeking medical treatment during a disaster is typically a small subset of the total number of those affected, the additional burden on health care facilities can be significant (Hess et al., 2009). Six weather and climate events that struck the USA between 2000 and 2009 were estimated to have increased health care costs by US$740 million, reflecting more than 760,000 encounters with the health care system (Knowlton et al., 2011). Hospitalizations, with attendant costs, can increase from cases of heat stress, heat stroke, and

Frequently Asked Questions

FAQ 10.3 | Are other economic sectors vulnerable to climate change too?

Economic activities such as agriculture, forestry, fisheries, and mining are exposed to the weather and thus vulnerable to climate change. Other economic activities, such as manufacturing and services, largely take place in controlled environments and are not really exposed to climate change. However, markets connect sectors so that the impacts of climate change spill over from one activity to all others. The impact of climate change on economic development and growth also affects all sectors.

acerbations of cardiorespiratory diseases and other health conditions during heat waves (e.g., Lin et al., 2012; Astrom et al., 2013), and from the adverse health impacts of other extreme events (Sections 11.4.1-2). For example, one trauma center in the USA found a 5% increase in hourly admissions for each approximately 5°C increase in temperature (Rising et al., 2006). Individuals looking for an air-conditioned location during high ambient temperatures can further increase hospital visits (Carthey et al., 2009).

Climate change is projected to increase the burden of major worldwide causes of childhood mortality, including malnutrition, diarrheal diseases, and malaria (Sections 11.5.1-2, 11.6.1). Any increase in health burdens or risks would increase the demands for public health services (e.g., surveillance and control programs) and the demands for health care and relevant supplies (e.g., antimalarials, insecticide-treated bednets, oral rehydration). Studies estimating the costs of additional cases of climate-sensitive health outcomes focus on the costs of treatment, typically omitting the costs of providing additional health services, implementing new policies, and health actions in other sectors (Hutton, 2011). Because most climate change-related cases of adverse health outcomes are projected to occur in low-income countries, treatment costs will primarily be borne by families where governments provide limited health care (WHO, 2004). Time off from work to care for sick children could affect productivity.

Public and private health expenditures account for approximately 10% of global GDP (http://data.worldbank.org/indicator/SH.XPD.TOTL.ZS). A systematic analysis of developing country government expenditures on health from domestic sources estimated that from 1995 to 2006, public financing of health in constant US$ increased nearly 100%; this was a product of rising GDP, slight decreases in the share of GDP spent by government, and increases in the share of government spending on health (Lu et al., 2010). The results varied by region, with shares of government expenditures on health increasing in many regions but decreasing in many sub-Saharan African countries. Development assistance for health rose from about US$8 billion (in constant US$[2007]) in 1995 to nearly US$19 billion in 2005 (Ravishankar et al., 2009). Domestic government spending on health was negatively affected by development assistance to governments and positively affected when assistance was to the non-governmental sector (Lu et al., 2010).

Estimates of the costs of treating future cases of adverse health outcomes from climate change are in the range of billions of US$ annually (Ebi, 2008; Pandey, 2010). An estimate of the worldwide costs in 2030 of additional cases of malnutrition, diarrheal disease, and malaria due to climate change—assuming no population or economic growth, emissions reductions resulting in stabilization at 750 ppm CO_2-eq in 2210, and current costs of treatment in developing countries—estimated treatment costs without adaptation could be US$4 to 12 billion worldwide, depending on assumptions of the sensitivity of these health outcomes to climate change (Ebi, 2008). The costs for additional infrastructure and health care workers were not estimated, nor were the costs of additional public health services, such as surveillance and monitoring. The costs were estimated to be unevenly distributed, with most of the costs borne by developing countries, particularly in Southeast Asia and Africa, to address the projected approximately 3 to 5% increase in the number of cases of diarrheal disease and malaria from the 2002 baseline (Markandya and Chaibai, 2009). The prevalence of these diseases have since declined (http://apps.who.int/gho/data/node.main.14?lang=en; Section 11.1.1), although there is considerable uncertainty in mortality data from many low-income countries because of the low proportion of deaths covered by vital registration programs (Byass et al., 2013).

A second global estimate assumed UN population projections, strong economic growth, updated projections of the current health burden of diarrheal diseases and malaria, two climate scenarios, and updated estimates of the costs of malaria treatment (Pandey, 2010). In 2010, the average annual adaptation costs for treating diarrheal disease and malaria were estimated to be US$3 to 5 billion, with the costs expected to decline over time with improvement in basic health services. Over the period 2010–2050, the average annual costs were estimated to be around US$2 billion, with most of the costs related to treating diarrheal disease; the largest burden is expected to be in sub-Saharan Africa. The differences in costs from Ebi (2008) are due primarily to a reduction in the baseline burden of disease and lower costs for malaria treatment.

Watkiss and Hunt (2012) estimated the health impacts of climate change in Europe in 2071–2100 using physical and monetary metrics, taking socioeconomic change into consideration. Temperature-related mortality during winter and summer due to climate change included positive and negative effects, with welfare costs (and benefits) of up to US$130 billion annually, with impacts unevenly distributed across countries. Assumptions about acclimatization influenced the size of the health impacts. The welfare costs for salmonellosis were estimated at potentially several hundred million euro annually, and those for the mental health impacts associated with coastal flooding due to climate change were up to approximately US$2 billion annually.

Estimated additional health care costs for climate change-related cases of malaria are similar in southern Africa (van Rensburg and Blignaut, 2002). Ranges for (low-high) additional cost scenarios for the prevention and treatment of malaria in South Africa in 2025 were estimated to be approximately US$280 to 3764 million. Estimates for Botswana and Namibia are US$9 to 124 million and US$13 to 177 million, respectively. The high cost scenario for Namibia is about 4.6% of GDP. The climate change-related malaria inpatient and outpatient treatments costs at the end of the century (2080–2100) in 25 African countries[1] indicated that even marginal changes in temperature and precipitation could affect the number of malaria cases, with increases in most countries and decreases in others (Egbendewe-Mondzozo et al., 2011). The end of century treatment costs as a proportion of annual 2000 health expenditures per 1000 people would increase in the vast majority of countries, with increases of more than 20% in inpatient treatment costs for Burundi, Côte D'Ivoire, Malawi, Rwanda, and Sudan.

The costs of treating cases of cholera in Tanzania due to climate change in 2030 were estimated to be in the range of 0.32 to 1.4% of GDP (Trærup et al., 2011), and there would be costs for treating additional cases of diarrhea and malaria in India in 2030, depending on the emission scenario (Ramakrishnan, 2011).

Bosello et al. (2006) used a computable general equilibrium model to study the economic impacts of climate-change-induced changes in mortality and morbidity due to cardiovascular and respiratory diseases, malaria, diarrhea, schistosomiasis, and dengue fever. They considered the effects on labor productivity and demand for health care, and found that health and welfare impacts have the same sign. The economy-wide health impacts were greater than simple aggregation of the costs of the individual health outcomes. Increased health problems were associated with an expansion of the public sector at the expense of the private sector.

Estimates of the impacts of climate change on worker productivity, assuming current work practices, primarily through heat stress, indicate that productivity has already declined during the hottest and wettest seasons in parts of Africa and Asia, with more than half of afternoon hours projected to be lost to the need for rest breaks in 2050 in Southeast Asia and up to a 20% loss in global productivity in 2100 under RCP4.5 (Kjellstrom et al., 2009, 2013; Dunne et al., 2013; see also Section 11.6.2). Alternate work practices may offer some relief from a health perspective, but would likely lead to significantly decreased productivity (Chapter 11).

10.9. Impacts on Markets and Development

Prior sections of this chapter present the direct impacts of climate change on the economy sector by sector. There are, however, also indirect impacts, from the one sector on the rest of the economy (Section 10.9.1) and on economic growth and development (Section 10.9.2).

[1] Algeria, Benin, Botswana, Burkina, Burundi, Central African Republic, Chad, Côte D'Ivoire, Djibouti, Egypt, Ethiopia, Ghana, Guinea, Malawi, Mali, Mauritania, Morocco, Niger, Rwanda, South Africa, Sudan, Togo, Uganda, Tanzania, Zimbabwe.

10.9.1. Effects of Markets

There are three channels through which economic impact diffuse. First, outputs of one sector are used as inputs to other sectors. For example, a change in crop yields would affect the food-processing industry. Second, products compete for the consumers' finite budget. If, for example, food becomes more expensive, a consumer would shift to cheaper food but also spend less money on other goods and services. Third, sectors compete for the primary factors of production (labor, capital, land, water). If, besides more fertilizers and irrigation, more labor is needed in agriculture to offset a drop in crop yields, less labor is available to produce other goods and services. Firms and households react to changes in relative prices, domestically and internationally. Ignoring these effects would lead to biased estimates of the impacts of climate change.

General equilibrium analysis describes how climate change impacts in one sector propagate to the rest of the economy, how impacts in one country influence other countries, and how macroeconomic conditions affect each impact (Ginsburgh and Keyzer, 1997). General equilibrium models can provide a comprehensive and internally consistent analysis of the medium-term impact of climate change on economic activity and welfare. However, these models necessarily make a number of simplifying assumptions, particularly with regard to the rationality of consumers and producers and the absence of market imperfections. Other types of economic models have yet to be applied to the estimation of indirect economic effects of climate change.

Computable general equilibrium models have long been used to study the wider economic implications of changes in crop yields. Yates and Strzepek (1998) show, for instance, that the impact of a reduced flow of the Nile on the economy of Egypt is much more severe without international trade than with, because trade would allow Egypt to focus on water-extensive production for export and import its food.

Older studies focused on the impact of climate change on patterns of specialization and trade, food prices, food security, and welfare (Kane et al., 1992; Reilly et al., 1994; Winters et al., 1998; Yates and Strzepek, 1998; Darwin and Kennedy, 2000; Darwin, 2004). This has been extended to land use (Lee, 2009; Ronneberger et al., 2009), water use (Kane et al., 1992; Calzadilla et al., 2011), and multiple stresses (Reilly et al., 2007). General equilibrium models have also been used to estimate the value of improved weather forecasts (Arndt and Bacou, 2000), a form of adaptation to climate change. Computable general equilibrium analysis has also been used to study selected impacts other than agriculture, notably SLR (Darwin and Tol, 2001; Bosello et al., 2007b), tourism (Berrittella et al., 2006; Bigano et al., 2008), human health (Bosello et al., 2006), and energy (see Section 10.2).

Bigano et al. (2008) study the joint, global impact on tourism and coasts in the 21st century, finding that changes in tourist demand dominate the welfare impacts of SLR. Kemfert (2002) and Eboli et al. (2010) estimate the joint, global effect on the world economy of a range of climate change impacts in the 21st century, but conflate general equilibrium and growth effects. Aaheim et al. (2010) analyze the economic effects of impacts of climate change on agriculture, forestry, fishery, energy demand, hydropower production, and tourism on the Iberian Peninsula. They find positive impacts on output in some sectors (agriculture,

10

electricity), negative impacts in other sectors (forestry, transport), and negligible ones in others (manufacturing, services). Ciscar et al. (2011) study the combined impact on agriculture, coasts, river floods, and tourism in the current European economy. They find an average welfare loss of 0.2 to 1.0% (depending on the SRES scenario) but there are large regional differences with losses in southern Europe and gains in northern Europe.

The following initial conclusions emerge. First, markets matter. Impacts are transmitted across locations—with local, regional, and global impacts—and across multiple sectors of the economy. For instance, landlocked countries are affected by SLR because their agricultural land increases in value as other countries face erosion and floods. Second, consumers and producers are often affected differently. The price increases induced by a reduction in production may leave producers better off while hurting consumers. Third, the distribution of the direct impacts can be very different than the distribution of the indirect effects. For instance, a loss of production may be advantageous to an individual company or country if the competition loses more. Fourth, a loss of productivity or productive assets in one sector leads to further losses in the rest of the economy. Fifth, markets offer options for adaptation, particularly possibilities for substitution. This changes the size, and sometimes the sign, of the impact estimate.

10.9.2. Aggregate Impacts

Since AR4, four new estimates of the global aggregate impact on human welfare of moderate climate change were published (Maddison and Rehdanz, 2011; Bosello et al., 2012; Roson and van der Mensbrugghe, 2012), including two estimates for warming greater than 3°C. Estimates agree on the size of the impact (small relative to economic growth), and 17 of the 20 impact estimates shown in Figure 10-1 are negative. Losses accelerate with greater warming, and estimates diverge. The new estimates have slightly widened the uncertainty about the economic impacts of climate.

Welfare impacts have been estimated with different methods, ranging from expert elicitation to econometric studies and simulation models. Different studies include different aspects of the impacts of climate change, but no estimate is complete; most experts speculate that excluded impacts are on balance negative. Estimates across the studies reflect different assumptions about inter-sectoral, inter-regional, and inter-temporal interactions, about adaptation, and about the monetary values of impacts. Aggregate estimates of costs mask significant differences in impacts across sectors, regions, countries, and populations. Relative to their income, economic impacts are higher for poorer people.

10.9.3. Social Cost of Carbon

The social cost of carbon (SCC) monetizes the expected welfare impacts of a marginal increase in carbon dioxide emissions in a given year (i.e., the welfare loss associated with an additional tonne of CO_2 emitted), aggregated across space, time, and probability (Tol, 2011). Figure 10-2 shows estimates published before AR4 and since, using the kernel density estimator by Tol (2013), extending the data with new estimates by Anthoff and Tol (2013b), Hope and Hope (2013), Hope (2013), and the Interagency Working Group on the Social Cost of Carbon (2013). Central estimates of the social cost of carbon have fallen slightly for all pure rates of time preference and the uncertainty has tightened, particularly for studies that use a pure rate of time preference of zero.

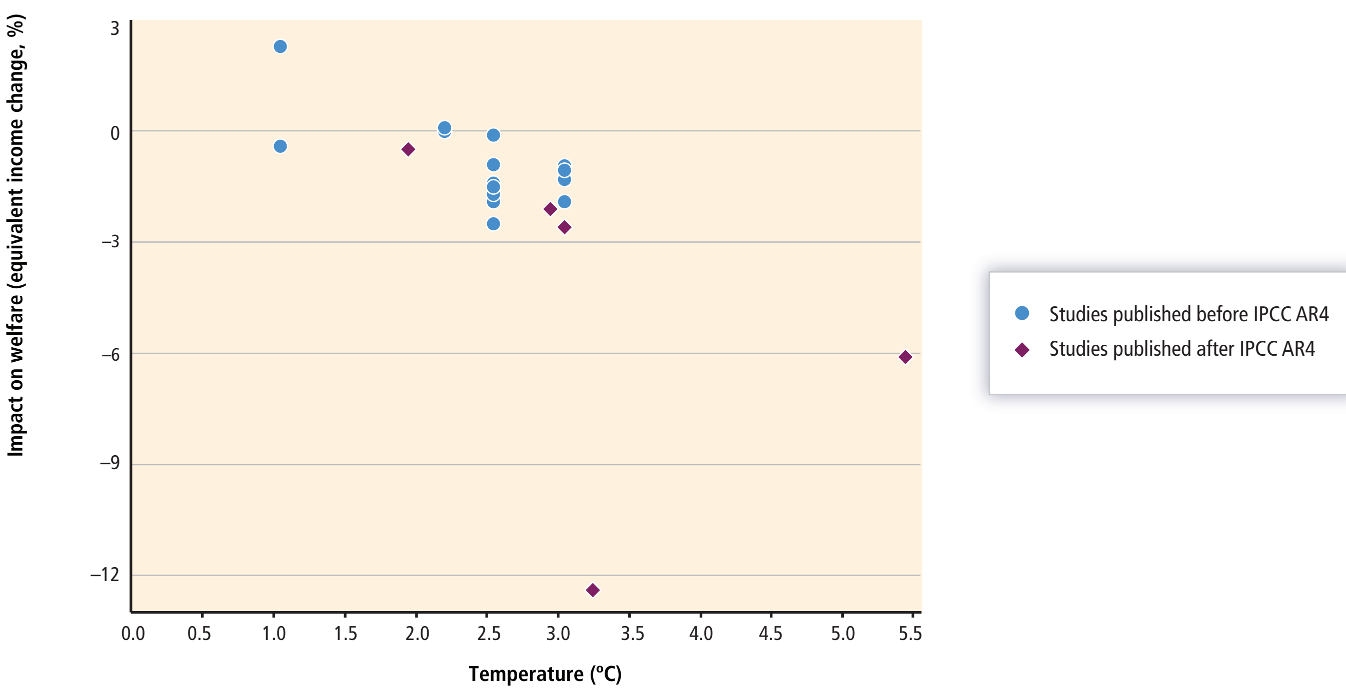


Figure 10-1 | Estimates of the total impact of climate change plotted against the assumed climate change (proxied by the increase in the global mean surface air temperature); studies published since IPCC AR4 are highlighted as diamonds; see Table SM10-1.

Table 10-9 | Selected statistical characteristics of the social cost of carbon: average (Avg) and standard deviation (SD), both in dollar per tonne of carbon, and number of estimates (*N*; number of studies in brackets).

PRTP	Post-AR4			Pre-AR4			All studies		
	Avg	SD	*N*	Avg	SD	*N*	Avg	SD	*N*
0%	270	233	97	745	774	89	585	655	142
1%	181	260	88	231	300	49	209	284	137
3%	33	29	35	45	39	42	40	36	186
All	241	233	462 (35)	565	822	323 (49)	428	665	785 (84)

Sources: See Section SM10.2 of the on-line supplementary material.

PRTP = pure rate of time preference.

See Table 10-9. For comparison, the EU ETS price in July 2013 was about US$21/tC.

Uncertainty in SCC estimates is high due to the uncertainty in underlying total damage estimates (see Section 10.9.2), uncertainty about future emissions, future climate change, future vulnerability and future valuation. The spread in estimates is also high due to disagreement regarding the appropriate framework for aggregating impacts over time (discounting), regions (equity weighing), and states of the world (risk aversion).

Quantitative analyses have shown that SCC estimates can vary by at least approximately two times depending on assumptions about future demographic conditions (Interagency Working Group on the Social Cost of Carbon, 2010), at least approximately three times owing to the incorporation of uncertainty (Kopp et al., 2012), and at least approximately four times owing to differences in discounting (Tol, 2011) or alternative damage functions (Ackerman and Stanton, 2012).

Concerns have been raised that the uncertainty about climate change is so large that the SCC would be unbounded (Weitzman, 2009), but this result is sensitive to assumptions about the utility function (Nordhaus, 2011; Buchholz and Schymura, 2012; Millner, 2013) and disappears when climate policy is formulated as balancing the risks of climate change against those of mitigation policy (Anthoff and Tol, 2013a; Hwang et al., 2013).

10.9.4. Effects on Growth

10.9.4.1. The Rate of Economic Growth

Climate change will also affect economic growth and development, but our understanding is limited. Fankhauser and Tol (2005) investigate four

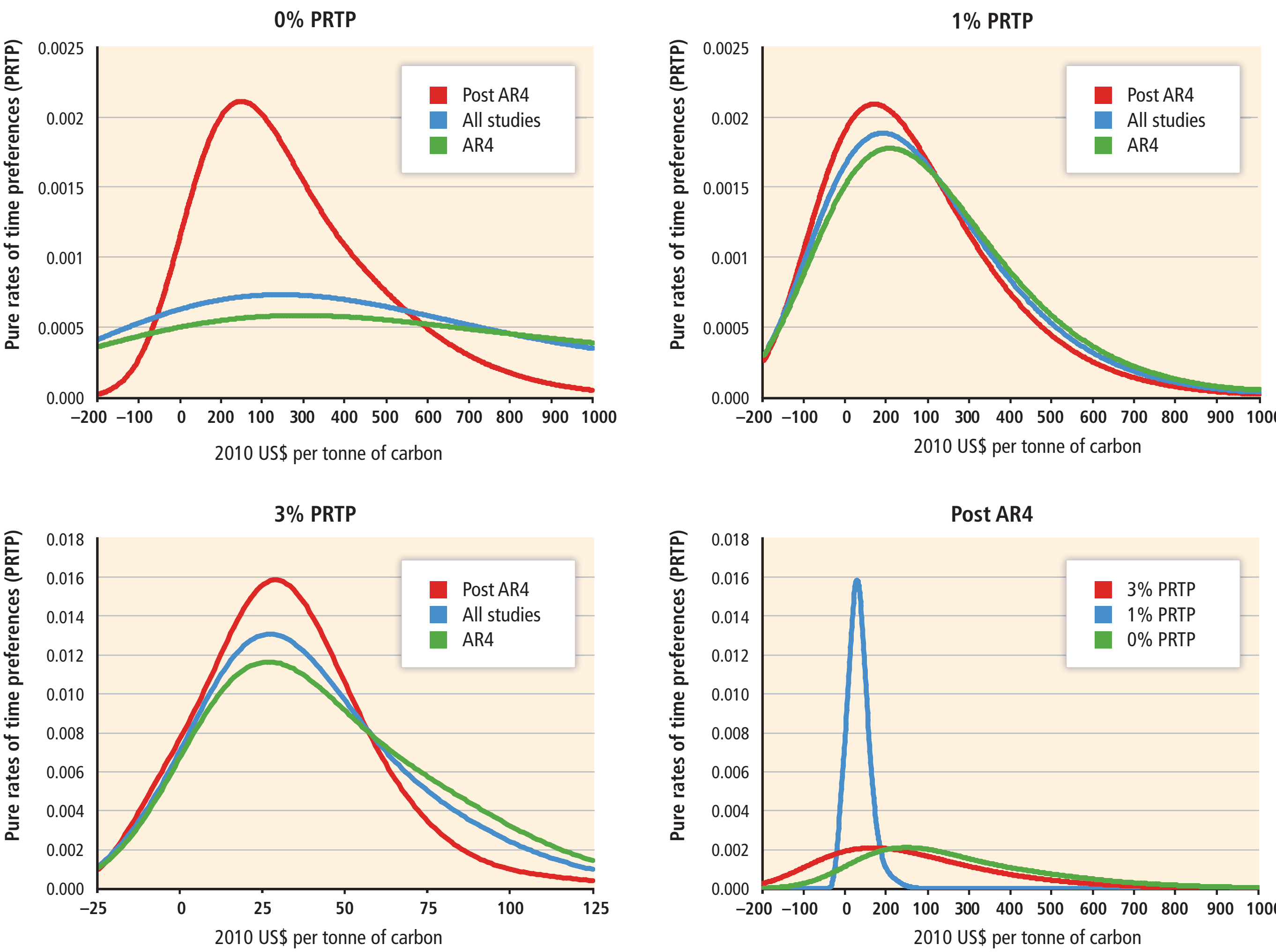


Figure 10-2 | Kernel densities of the social cost of carbon for all studies and studies before or after AR4 for three alternative pure rates of time preference (PRTP).

standard models of economic growth and three transmission mechanisms: economic production, capital depreciation, and the labor force. They find that, in three models, the fall in economic output is slightly larger than the direct impact on markets while in the fourth model (which emphasizes human capital accumulation) indirect impacts are 1.5 times as large. The difference can be understood as follows. In the three models, the impacts of climate change crowd out consumption and investment in physical capital, while in the fourth model investment in human capital is also crowded out; lower investment implies slower growth. Hallegatte (2005) reaches a similar conclusion. Hallegatte and Thery (2007), Hallegatte and Ghil (2008), and Hallegatte and Dumas (2009) highlight that the impact of climate change through natural hazards on economic growth can be amplified by market imperfections and the business cycle. In addition, Eboli et al. (2010) use a multi-sector, multi-region growth model, and find that the impact of climate change would lead to a 0.3% reduction of global GDP in 2050. Regional impacts are more pronounced, ranging from –1.0% in developing countries to +0.4% in Australia and Canada. In contrast, Garnaut (2008) finds –2.1% for Australia; the difference is due mainly to impacts on infrastructure (cf. Section 10.4). Sectoral results are varied too, with output changes ranging from +0.5% for power generation (to meet increased demand to air conditioning) to –0.7% for natural gas (as demand for space heating falls).

Using a biophysical model of the human body's ability to do work, Kjellstrom et al. (2009) find that by the end of the century climate change may reduce labor productivity by 11 to 27% in the humid (sub)tropics (depending on the SRES scenario; see Chapter 11 for further discussion). Assuming an output elasticity of labor of 0.8, this would reduce economic output in the affected sectors (involving heavy manual labor without air conditioning) by 8 to 22%. Although structural changes in the economy may well reduce the dependence on manual labor and air conditioning would be an effective adaptation, even the ameliorated impact would have a substantial, but as yet unquantified, impact on economic growth.

There are also statistical analyses of the relationship between climate and economic growth. Barrios et al. (2010) find that the decline in rainfall in the 20th century partly explains the economies of sub-Saharan Africa have grown more slowly than those of other developing regions. Brown et al. (2011) corroborate this. Dell et al. (2012) find that, in the second half of the 20th century, anomalously hot weather slowed down economic growth in poor countries, in both the agricultural and the industrial sectors. Dell et al. (2009) find that 1°C of warming would reduce income by 1.1% in the short run, and by 0.5% in the long run. The difference is due to adaptation. Horowitz (2009) finds a much larger effect: a 3.8% drop in income in the long run for one degree of warming. The impact of natural disasters on economic growth in the long-term is disputed, with studies reporting positive effects (Skidmore and Toya, 2002), negative effects (Raddatz, 2009), and no discernible effects (Cavallo et al., 2013).

10.9.4.2. Poverty Traps

Poverty is concentrated in the tropics and subtropics. This has led some analysts to the conclusion that a tropical climate is one in a complex of causes of poverty (which itself is a cause of poverty). We here focus on national economies, while Chapter 13 discusses groups of people in poverty. Gallup et al. (1999) emphasize the link between climate, disease, and poverty while Masters and McMillan (2001) focus on climate, agricultural pests, and poverty. Other studies (Acemoglu et al., 2001, 2002; Easterly and Levine, 2003) argue that climatic influence on development disappears if differences in human institutions (the rule of law, education, etc.) are accounted for. However, Van der Vliert (2008) demonstrates that climate affects human culture and thus institutions, but this has yet to be explored in the economic growth literature. Brown et al. (2011) find that weather affects economic growth in sub-Saharan Africa—particularly, drought decelerates growth. Jones and Olken (2010) find that exports from poor countries fall during hot years. Bloom et al. (2003) find limited support for an impact of climate (rather than weather) on past growth in a single-equilibrium model, but strong support in a multiple-equilibrium model: hot and wet conditions and large variability in rainfall reduce long-term growth in poor countries (but not in hot ones) and increase the probability of being poor.

Galor and Weil (1996) speculate about the existence of a climate-health-poverty trap. Strulik (2008), Bonds et al. (2010), Bretschger and Valente (2011), Gollin and Zimmermann (2012), and Ikefuji and Horii (2012) posit theoretical models and offer limited empirical support, while Tang et al. (2009) offers more rigorous empirical evidence. This is further supported by yet-to-be-published analyses (Gollin and Zimmermann, 2008; Ikefuji et al., 2010). Climate-related diseases such as malaria and diarrhea impair children's cognitive and physical development. This contributes to poverty in their later life so that there are limited means to protect their own children against these diseases. Furthermore, high infant mortality may induce parents to have many children so that the investment in education is spread thin. An increase in infant and child mortality and morbidity due to climate change could thus trap more people in poverty.

Zimmerman and Carter (2003) build a model in which the risk of natural disasters causes a poverty trap: at higher risk levels, households prefer assets with a safe but low return. Carter et al. (2007) find empirical support for this model at the household level, but van den Berg (2010) concludes the natural disaster itself has no discernible impact on investment choices. At the macroeconomic level, natural disasters disproportionally affect the growth rate of poor countries (Noy, 2009).

Devitt and Tol (2012) construct a model with a conflict-poverty trap, and show that climate change may exacerbate this. Bougheas et al. (1999, 2000) show that more expensive infrastructure, for example, because of frequent repairs after natural disasters, slows down economic growth and that there is a threshold infrastructure cost above which trade and specialization do not occur, suggesting another mechanism through which climate could cause a poverty trap. The implications of climate change have yet to be assessed.

10.9.5. Summary

In sum, estimates of the aggregate economic impact of climate change are relatively small but with a large downside risk. Estimates of the incremental damage per tonne of CO_2 emitted vary by two orders of magnitude, with the assumed discount rate the main driver of the differences between estimates. The literature on the impact of climate and climate change on economic growth and development has yet to reach firm conclusions. There is agreement that climate change would slow economic growth, by a little according to some studies and by a lot according to other studies. Different economies will be affected differently. Some studies suggest that climate change may trap more people in poverty.

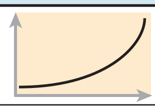
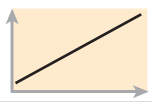
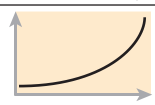
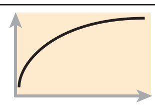
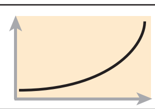
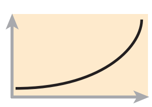
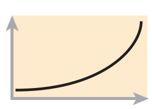
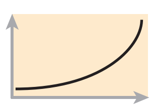
10.10. Summary; Research Needs and Priorities

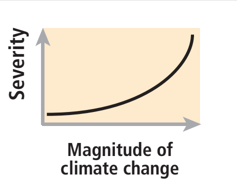
Table 10-10 summarizes the main findings. For each of the sectors discussed above, it gives the main climate drivers, the relationship between climate and impact (limited to less than linear, linear, and more than linear), the sign of the impacts (where needed split by economic actor), drivers other than climate change, and the relative importance of climate change.

Evaluating the economic aspects of the impacts has emerged as an active research area. Initial work has developed in a few key economic sectors and through economy-wide economic assessments. Data, tools, and methods continue to evolve to address additional sectors and more complex interactions among the sectors in the economic systems and a changing climate.

Based on a comprehensive assessment across economic sectors, few key sectors have been subject to detailed research. Multiple aspects of energy impacts have been assessed, but others remain to be evaluated, particularly economic impact assessments of adaptation both on existing and future infrastructure, but also the costs and benefits for future systems under differing climatic conditions. Studies focused on the impacts of

Table 10-10 | Summary of findings.

Sector	Climate change drivers	Sensitivity to climate change	Sign	Other drivers	Relative impact of climate change to other drivers
Winter tourism	• Temperature • Snow		Negative	• Population • Lifestyle • Income • Aging	Much less
Summer tourism	• Temperature • Rainfall • Cloudiness		Negative for suppliers in low altitudes and latitudes Positive for suppliers in high altitudes and latitudes Neutral for tourists	• Population • Income • Lifestyle • Aging	Much less
Cooling demand	• Temperature • Humidity • Hot spells		Positive for suppliers Negative for consumers	• Population • Income • Energy prices • Technology change	Less
Heating demand	• Temperature • Humidity • Cold spells		Negative for suppliers Positive for consumers	• Population • Income • Energy prices • Technology change	Less
Health services	• Temperature • Precipitation		Positive for suppliers Negative for consumers	• Aging • Income • Diet/lifestyle	Less
Water infrastructure and services	• Temperature • Precipitation • Storm Intensity • Seasonal Variability		Negative for water users Positive for suppliers Spatially heterogeneous	• Population • Income • Urbanization • Regulation	Less in developing countries Equal in developed countries
Transportation	• Temperature • Precipitation • Storm intensity • Seasonal variability • Freeze/thaw cycles		Negative for all users Positive for transport construction industry	• Population • Income • Urbanization • Regulation • Mode shifting • Consumer and commuter behavior	Much less in developing countries Less in developed countries
Insurance	• Temperature • Precipitation • Storm intensity • Seasonal variability • Freeze/thaw cycles		Negative for consumers Neutral for suppliers	• Population • Income • Regulation • Product innovation	Less or equal in developing countries Equal or more in developed countries



climate change on the energy sector indicate both potential benefits and detrimental impacts across developed and developing countries. In energy supply, the deployment of extraction, transport and processing infrastructure, power plants, and other installations are expected to proceed rapidly in developing countries in the coming decades to satisfy fast growing demand for energy. Designing newly deployed facilities with a view to projected changes in climate attributes and extreme weather patterns would require targeted inquiries into the impacts of climate change on the energy-related resource base, conversion, and transport technologies.

The economics of climate change impacts on transportation systems and their role in overall economic activity have yet to be well understood. For water related sectors, improved estimation of flood damages to economic sectors, research on economic impacts of ecosystems, rivers, lakes and wetlands, ecosystems service, and tourism and recreation are needed. Economic assessments of adaptation strategies such as water savings technologies, particularly for semiarid and arid developing countries, are also needed. Further, detailed studies are needed of the integrated impact of climate change on all water-dependent economic sectors, as existing studies do not examine competitiveness between water uses among sectors and economic productivity.

Although both tourism and recreation are sensitive to climate change, the literature on tourism is far more extensive. Current studies either have a rudimentary representation of the effect of weather and climate but a detailed representation of substitution between holiday destination and activities, or a detailed representation of the immediate impact of climate change but a rudimentary representation of alternatives to the affected destinations or activities.

Considerable research has been developed related to climate change impacts on insurance; however, only limited research is available on observed and projected changes in insured climate-related losses. To advance such research, climate science and risk research communities need to be better integrated. In addition, only few quantitative projection studies exist on regional markets including scenarios of changing hazard properties, exposure, vulnerability and adaption status, regulation, and availability of risk-based capital to indemnify disaster losses. Little research is available on the implications of climate change for banking/investment activities, in particular regarding the direct exposure of financial infrastructure. But also indirect effects through value losses in loan portfolios and assets as a result of physical damage and regulatory/reputational effects, together with liability and litigation risks, are under-investigated.

Little literature exists on potential climate impacts on other economic sectors, such as mining, manufacturing, and services (apart from health, insurance, and tourism), in particular assessments of whether these sectors are indeed sensitive to climate and climate change.

The spillover effects of the impacts of climate change in one sector on other markets are understood in principle, but the number of quantitative studies is too few to place much confidence in the numerical results. Similarly, the impact of climate and climate change on economic growth and development is not well understood, with some studies pointing to a small or negligible effect and other studies arguing for a large or dominant effect. A limited set of studies have evaluated the aggregate economic impact of climate change up to 3°C annual mean temperature rise, while only one study has evaluated larger temperature scenarios, suggesting considerable new analysis is warranted to improve confidence in the conclusions and investigation of a broader suite of Representative Concentration Pathways (RCPs).

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11

Human Health: Impacts, Adaptation, and Co-Benefits

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Executive Summary

The health of human populations is sensitive to shifts in weather patterns and other aspects of climate change (*very high confidence*). These effects occur directly, due to changes in temperature and precipitation and occurrence of heat waves, floods, droughts, and fires. Indirectly, health may be damaged by ecological disruptions brought on by climate change (crop failures, shifting patterns of disease vectors), or social responses to climate change (such as displacement of populations following prolonged drought). Variability in temperatures is a risk factor in its own right, over and above the influence of average temperatures on heat-related deaths. {11.4} Biological and social adaptation is more difficult in a highly variable climate than one that is more stable. {11.7}

Until mid-century climate change will act mainly by exacerbating health problems that already exist (*very high confidence*). New conditions may emerge under climate change (*low confidence*), and existing diseases (e.g., food-borne infections) may extend their range into areas that are presently unaffected (*high confidence*). But the largest risks will apply in populations that are currently most affected by climate-related diseases. Thus, for example, it is expected that health losses due to climate change-induced undernutrition will occur mainly in areas that are already food-insecure. {11.3}

In recent decades, climate change has contributed to levels of ill health (*likely*) though the present worldwide burden of ill health from climate change is relatively small compared with other stressors on health and is not well quantified. Rising temperatures have increased the risk of heat-related death and illness (*likely*). {11.4} Local changes in temperature and rainfall have altered distribution of some water-borne illnesses and disease vectors, and reduced food production for some vulnerable populations (*medium confidence*). {11.5-6}

If climate change continues as projected across the Representative Concentration Pathway (RCP) scenarios, the major changes in ill health compared to no climate change will occur through:

- Greater risk of injury, disease, and death due to more intense heat waves and fires (*very high confidence*) {11.4}
- Increased risk of undernutrition resulting from diminished food production in poor regions (*high confidence*) {11.6}
- Consequences for health of lost work capacity and reduced labor productivity in vulnerable populations (*high confidence*) {11.6}
- Increased risks of food- and water-borne diseases (*very high confidence*) and vector-borne diseases (*medium confidence*) {11.5}
- Modest reductions in cold-related mortality and morbidity in some areas due to fewer cold extremes (*low confidence*), geographical shifts in food production, and reduced capacity of disease-carrying vectors due to exceedance of thermal thresholds (*medium confidence*). These positive effects will be increasingly outweighed, worldwide, by the magnitude and severity of the negative effects of climate change (*high confidence*). {11.4-6}

Impacts on health will be reduced, but not eliminated, in populations that benefit from rapid social and economic development (*high confidence*), particularly among the poorest and least healthy groups (*very high confidence*). {11.4, 11.6-7} Climate change is an impediment to continued health improvements in many parts of the world. If economic growth does not benefit the poor, the health effects of climate change will be exacerbated.

In addition to their implications for climate change, essentially all the important climate-altering pollutants (CAPs) other than carbon dioxide (CO_2) have near-term health implications (*very high confidence*). In 2010, more than 7% of the global burden of disease was due to inhalation of these air pollutants (*high confidence*). {Box 11-4}

Some parts of the world already exceed the international standard for safe work activity during the hottest months of the year. The capacity of the human body to thermoregulate may be exceeded on a regular basis, particularly during manual labor, in parts of the world during this century. In the highest Representative Concentration Pathway, RCP8.5, by 2100 some of the world's land area will be experiencing 4°C to 7°C higher temperatures due to anthropogenic climate change (WGI AR5 Figure SPM.7). If this occurs, the combination of high temperatures and high humidity will compromise normal human activities, including growing food or working outdoors in some areas for parts of the year (*high confidence*). {11.8}

The most effective measures to reduce vulnerability in the near term are programs that implement and improve basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*). {11.7} In addition, there has been progress since AR4 in targeted and climate-specific measures to protect health, including enhanced surveillance and early warning systems. {11.7}

There are opportunities to achieve co-benefits from actions that reduce emissions of warming CAPs and at the same time improve health. Among others, these include:

- Reducing local emissions of health-damaging and climate-altering air pollutants from energy systems, through improved energy efficiency, and a shift to cleaner energy sources (*very high confidence*) {11.9}
- Providing access to reproductive health services (including modern family planning) to improve child and maternal health through birth spacing and reduce population growth, energy use, and consequent CAP emissions over time (*medium confidence*) {11.9}
- Shifting consumption away from animal products, especially from ruminant sources, in high-meat-consumption societies toward less CAP-intensive healthy diets (*medium confidence*) {11.9}
- Designing transport systems that promote active transport and reduce use of motorized vehicles, leading to lower emissions of CAPs and better health through improved air quality and greater physical activity (*high confidence*). {11.9}

There are important research gaps regarding the health consequences of climate change and co-benefits actions, particularly in low-income countries. There are now opportunities to use existing longitudinal data on population health to investigate how climate change affects the most vulnerable populations. Another gap concerns the scientific evaluation of the health implications of adaptation measures at community and national levels. A further challenge is to improve understanding of the extent to which taking health co-benefits into account can offset the costs of greenhouse gas mitigation strategies.

11.1. Introduction

This chapter examines what is known about the effects of climate change on human health and, briefly, the more direct impacts of climate-altering pollutants (CAPs; see Glossary) on health. We review diseases and other aspects of poor health that are sensitive to weather and climate. We examine the factors that influence the susceptibility of populations and individuals to ill health due to variations in weather and climate, and describe steps that may be taken to reduce the impacts of climate change on human health. The chapter also includes a section on health "co-benefits." Co-benefits are positive effects on human health that arise from interventions to reduce emissions of those CAPs that warm the planet or vice versa.

This is a scientific assessment based on best available evidence according to the judgment of the authors. We searched the English-language literature up to August 2013, focusing primarily on publications since 2007. We drew primarily (but not exclusively) on peer-reviewed journals. Literature was identified using a published protocol (Hosking and Campbell-Lendrum, 2012) and other approaches, including extensive consultation with technical experts in the field. We examined recent substantial reviews (e.g., Gosling et al., 2009; Bassil and Cole, 2010; Hajat et al., 2010; Huang et al., 2011; McMichael, 2013b; Stanke et al., 2013) to check for any omissions of important work. In selecting citations for the chapter, we gave priority to publications that were recent (since AR4), comprehensive, added significant new findings to the literature, and included areas or population groups that have not previously been well described or were judged to be particularly policy relevant in other respects.

We begin with an outline of measures of human health, the major driving forces that act on health worldwide, recent trends in health status, and health projections for the remainder of the 21st century.

11.1.1. Present State of Global Health

The Fourth Assessment Report (AR4) pointed to dramatic improvement in life expectancy in most parts of the world in the 20th century, and this trend has continued through the first decade of the 21st century (Wang et al., 2012). Rapid progress in a few countries (especially China) has dominated global averages, but most countries have benefited from substantial reductions in mortality. There remain sizable and avoidable inequalities in life expectancy within and between nations in terms of education, income, and ethnicity (Beaglehole and Bonita, 2008) and in some countries, official statistics are so patchy in quality and coverage that it is difficult to draw firm conclusions about health trends (Byass, 2010). Years lived with disability have tended to increase in most countries (Salomon et al., 2012).

If economic development continues as forecast, it is expected that mortality rates will continue to fall in most countries; the World Health Organization (WHO) estimates the global burden of disease (measured in disability adjusted life years per capita) will decrease by 30% by 2030, compared with 2004 (WHO, 2008a). The underlying causes of global poor health are expected to change substantially, with much greater prominence of chronic diseases and injury; nevertheless, the major infectious diseases of adults and children will remain important in some regions, particularly sub-Saharan Africa and South Asia (Hughes et al., 2011).

11.1.2. Developments Since AR4

The relevant literature has grown considerably since publication of AR4. For instance, the annual number of MEDLINE citations on climate change and health doubled between 2007 and 2009 (Hosking and Campbell-Lendrum, 2012). In addition, there have been many reviews, reports, and international assessments that do not appear in listings such as MEDLINE but include important information nevertheless, for instance, the World Development Report 2010 (World Bank, 2010) and the 2011 UN Habitat report on cities and climate change (UN-HABITAT, 2011). Since AR4, there have been improvements in the methods applied to investigate climate change and health. These include more sophisticated modeling of possible future impacts (e.g., work linking climate change, food security, and health outcomes; Nelson et al., 2010) and new methods

Box 11-1 | Weather, Climate, and Health: A Long-Term Observational Study in African and Asian Populations

Given the dearth of scientific evidence of the relationship between weather/climate and health in low- and middle-income countries, we report on a project that spans sub-Saharan Africa and Asia. The INDEPTH Network currently includes 43 surveillance sites in 20 countries. Using standardized health and demographic surveillance systems, member sites have collected up to 45 years of information on births, migrations, and deaths. Currently, there are about 3.2 million people under surveillance (Sankoh and Byass, 2012).

To study relationships between weather and health, the authors obtained daily meteorological data for 12 INDEPTH populations between 2000 and 2009, and projected future climate changes to 2100 under the SRES A1B, A3, and B1 scenarios (Hondula et al., 2012). The authors concluded the health of all the populations would be challenged by the new climatic conditions, especially later in the century. In another study from the Network, Diboulo et al. (2012) examined the relation between weather and all-cause mortality data in Burkina Faso. Relations between daily temperature and mortality were similar to those reported in many high-income settings, and susceptibility to heat varied by age and gender.

to model the effects of heat on work capacity and labor productivity (Kjellstrom et al., 2009b). Other developments include coupling of high-quality, longitudinal mortality data sets with down-scaled meteorological data, in low-income settings (e.g., through the INDEPTH Network; see Box 11-1).

Since AR4, studies of the ways in which policies to reduce greenhouse gas (GHG) emissions may affect health, or vice versa, leading to so-called "co-benefits" in the case of positive outcomes for either climate or health, have multiplied (Haines et al., 2009).

Much has been written on links between climate, socioeconomic conditions, and health—for example, related to occupational heat exposure (Kjellstrom et al., 2009b) and malaria (e.g., Gething et al., 2010; Béguin et al., 2011). There is also growing appreciation of the social upheaval and damage to population health that may arise from the interaction of large-scale food insecurity, population dislocation, and conflict (see Chapter 12).

11.1.3. Non-Climate Health Effects of Climate-Altering Pollutants

CAPs affect health in other ways than through climate change, just as carbon dioxide (CO_2) creates non-climate effects such as ocean acidification. The effects of rising CO_2 levels on calcifying marine species are well documented and the risks for coral reefs are now more closely defined than they were at the time of the AR4 (see Chapter 30). There are potential implications for human health, such as undernutrition in coastal populations that depend on local fish stocks, but, so far, links between health and ocean acidification have not been closely studied (Kite-Powell et al., 2008). CAPs such as black carbon and tropospheric ozone have substantial, direct, negative effects on human health (Wang et al., 2013; see Section 11.5.3 and Box 11-3). Although CO_2 is not considered a health-damaging air pollutant at levels experienced outside particular occupational and health-care settings, one study has reported a reduction in mental performance at 1000 ppm and above, within the range that all of humanity would experience in some extreme climate scenarios by 2100 (Satish et al., 2012).

11.2. How Climate Change Affects Health

There are three basic pathways by which climate change affects health (Figure 11-1), and these provide the organization for the chapter:

- Direct impacts, which relate primarily to changes in the frequency of extreme weather including heat, drought, and heavy rain (Section 11.4)
- Effects mediated through natural systems, for example, disease vectors, water-borne diseases, and air pollution (Section 11.5)
- Effects heavily mediated by human systems, for example, occupational impacts, undernutrition, and mental stress (Section 11.6).

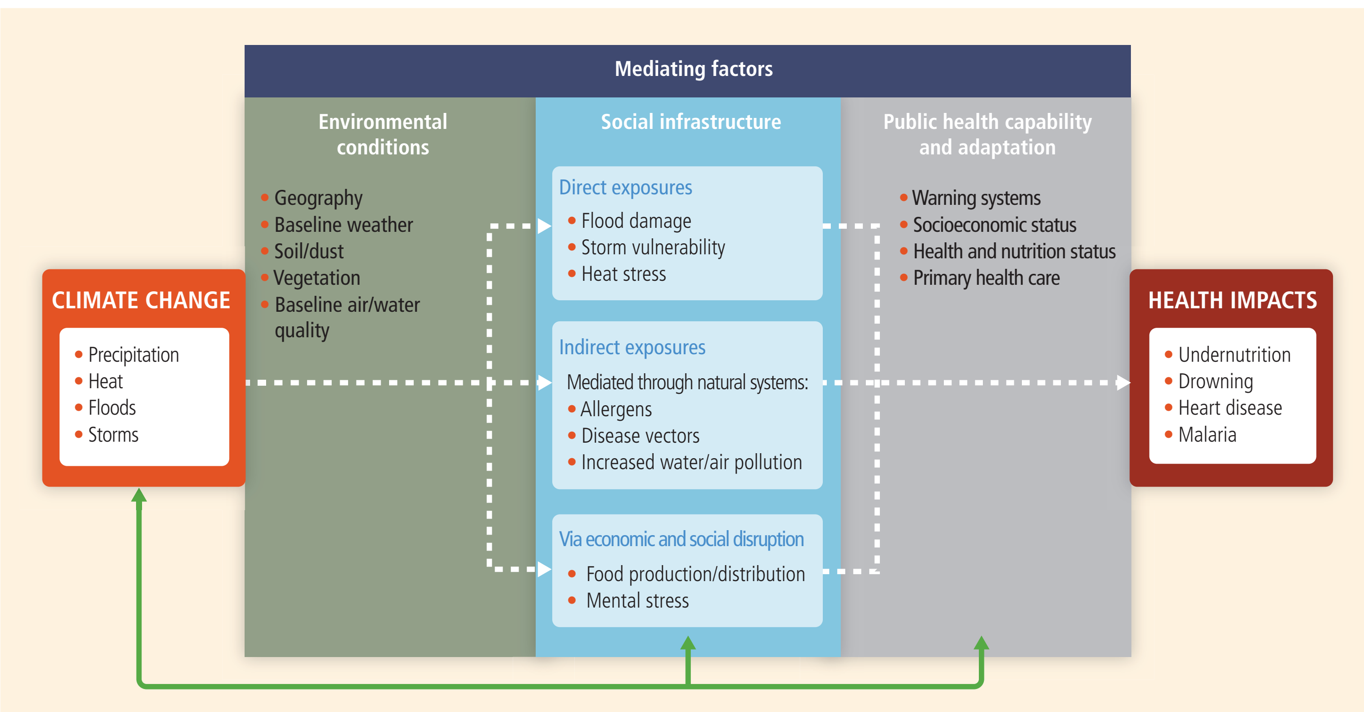

Figure 11-1 | Conceptual diagram showing three primary exposure pathways by which climate change affects health: directly through weather variables such as heat and storms; indirectly through natural systems such as disease vectors; and pathways heavily mediated through human systems such as undernutrition. The green box indicates the moderating influences of local environmental conditions on how climate change exposure pathways are manifest in a particular population. The gray box indicates that the extent to which the three categories of exposure translate to actual health burden is moderated by such factors as background public health and socioeconomic conditions, and adaptation measures. The green arrows at the bottom indicate that there may be feedback mechanisms, positive or negative, between societal infrastructure, public health, and adaptation measures and climate change itself. As discussed later in the chapter, for example, some measures to improve health also reduce emissions of climate-altering pollutants, thus reducing the extent and/or pace of climate change as well as improving local health (courtesy of E. Garcia, UC Berkeley). The examples are indicative.

The negative effects of climate change on health may be reduced by improved health services, better disaster management, and poverty alleviation, although the cost and effort may be considerable (Section 11.7). The consequences of large magnitude climate change beyond 2050, however, would be much more difficult to deal with (Section 11.8). Although there are exceptions, to a first approximation climate change acts to exacerbate existing patterns of ill health, by acting on the underlying vulnerabilities that lead to ill health even without climate change. Thus, before pursuing the three pathways in Figure 11-1, we summarize what is known about vulnerability to climate-induced illness and injury.

11.3. Vulnerability to Disease and Injury Due to Climate Variability and Climate Change

In the IPCC assessments, vulnerability is defined as the propensity or predisposition to be adversely affected (see Chapter 19 and Glossary). In this section, we consider causes of vulnerability to ill health associated with climate change and climate variability, including individual and population characteristics and factors in the physical environment.

We have outlined the causes of vulnerability separately, but in practice causes combine, often in a complex and place-specific manner. There are some factors (such as education, income, health status, and responsiveness of government) that act as generic causes of vulnerability. For example, the quality of governance—how decisions are made and put into practice—affects a community's response to threats of all kinds (Bowen et al., 2012; see Chapter 12). The background climate-related disease rate of a population is often the best single indicator of vulnerability to climate change—doubling of risk of disease in a low disease population has much less absolute impact than doubling of the disease when the background rate is high. (Note that here, and elsewhere in the chapter, we treat "risk" in the epidemiological sense: the probability that an event will occur.) But the precise causes of vulnerability, and therefore the most relevant adaptation capacities, vary greatly from one setting to another. For example, severe drought in Australia has been linked to psychological distress—but only for those residing in rural and remote areas (Berry et al., 2010). The link between high ambient temperatures and increased incidence of salmonella food poisoning has been demonstrated in many places (e.g., Zhang et al., 2010), but the lag varies from one country to another, suggesting that the mechanisms differ. Deficiencies in food storage may be the critical link in some places; food handling problems may be most important elsewhere (Kovats et al., 2004).

The 2010 World Development Report concluded that all developing regions are vulnerable to economic and social damage resulting from climate change—but for different reasons (World Bank, 2010). The critical factors for sub-Saharan Africa, for example, are the current climate stresses (in particular, droughts and floods) that may be amplified in parts of the region under climate change, sparse infrastructure, and high dependence on natural resources (see Chapter 22). Asia and the Pacific, on the other hand, are distinguished by the very large number of people living in low-lying areas prone to flooding (see Chapters 24 and 29).

11.3.1. Geographic Causes of Vulnerability

Location has an important influence on the potential for health losses caused by climate change (Samson et al., 2011). Those working outdoors in countries where temperatures in the hottest time of the year are already at the limits of thermal tolerance for part of the year will be more severely affected by further warming than workers in cooler countries (Kjellstrom et al., 2013). The inhabitants of low-lying coral atolls are very sensitive to flooding, contamination of freshwater reservoirs due to sea level rise, and salination of soil, all of which may have important effects on health (Nunn, 2009). Rural populations that rely on subsistence farming in low rainfall areas are at high risk of undernutrition and water-related diseases if drought occurs, although this vulnerability may be modified strongly by local factors, such as access to markets and irrigation facilities (Acosta-Michlik et al., 2008). Living in rural and remote areas may confer increased risk of ill health because of limited access to services and generally higher levels of social and economic disadvantage (Smith, 2008). Populations that are close to the present limits of transmission of vector-borne diseases are most vulnerable to changes in the range of transmission as a result of rising temperatures and altered patterns of rainfall, especially when disease control systems are weak (Zhou et al., 2008; Lozano-Fuentes et al., 2012.). In cities, those who live on urban heat islands are at greater risk of ill health due to extreme heat events (Stone et al., 2010; Uejio et al., 2011).

11.3.2. Current Health Status

Climate extremes may promote the transmission of certain infectious diseases, and the vulnerability of populations to these diseases will depend on the baseline levels of pathogens and their vectors. In the USA, as one example, arboviral diseases such as dengue are rarely seen after flooding, compared with the experience in other parts of the Americas. The explanation lies in the scarcity of dengue (and other pathogenic viruses) circulating in the population, before the flooding (Keim, 2008). On the other hand, the high prevalence of HIV infection in many populations in sub-Saharan Africa will tend to multiply the health risks of climate change, due to the interactions between chronic ill health, poverty, extreme weather events, and undernutrition (Ramin and McMichael, 2009). Chronic diseases such as diabetes and ischemic heart disease magnify the risk of death or severe illness associated with high ambient temperatures (Basu and Ostro, 2008; Sokolnicki et al., 2009).

11.3.3. Age and Gender

Children, young people, and the elderly are at increased risk of climate-related injury and illness (Perera, 2008). For example, adverse effects of malaria, diarrhea, and undernutrition are presently concentrated among children, for reasons of physiological susceptibility (Michon et al., 2007). In principle, children are thought to be more vulnerable to heat-related illnesses, owing to their small body mass to surface area ratio, but evidence of excess heat-related mortality in this age group is mixed (Basu and Ostro, 2008; Kovats and Hajat, 2008). Maternal antibodies acquired *in utero* provide some protection against dengue fever in the first year of life, but if infection does occur in infants it is more likely to provoke the severe hemorrhagic form of illness (Ranjit and Kissoon, 2011). Children are generally at greater risk when food supplies are restricted: households with children tend to have lower than average incomes, and food insecurity is associated with a range of adverse health outcomes among young children (Cook and Frank, 2008).

Older people are at greater risk from storms, floods, heat waves, and other extreme events (Brunkard et al., 2008), in part because they tend to be less mobile than younger adults and so find it more difficult to avoid hazardous situations and also because they are more likely to live alone in some cultures. Older people are also more likely to suffer from health conditions that limit the body's ability to respond to stressors such as heat and air pollution (Gamble et al., 2013).

The relationship between gender and vulnerability is complex. Worldwide, mortality due to natural disasters, including droughts, floods, and storms, is higher among women than men (WHO, 2011). However, there is variation regionally. In the USA, males are at greater risk of death following flooding (Jonkman and Kelman, 2005). A study of the health effects of flooding in Hunan province, China, also found an excess of flood deaths among males, often related to rural farming (Abuaku et al., 2009). In Canada's Inuit population males are exposed to dangers associated with insecure sea ice, while females may be more vulnerable to the effects of diminished food supplies (Pearce et al., 2011). In the Paris 2003 heat wave, excess mortality was greater among females overall, but there were more excess deaths among men in the working age span (25 to 64) possibly due to differential exposures to heat in occupational settings (Fouillet et al., 2006). In Bangladesh, females are more affected than males by a range of climate hazards, due to differences in prevalence of poverty, undernutrition, and exposure to water-logged environments (Neelormi et al., 2009). The effect of food insecurity on growth and development in childhood may be more damaging for girls than boys (Cook and Frank, 2008).

Pregnancy is a period of increased vulnerability to a wide range of environmental hazards, including extreme heat (Strand et al., 2012) and infectious diseases such as malaria, foodborne infections, and influenza (Van Kerkhove et al., 2011).

11.3.4. Socioeconomic Status

The poorest countries and regions are generally most susceptible to damage caused by climate extremes and climate variability (Malik et al., 2012), but wealthy countries are not immune, as shown by the deaths resulting from bushfires in Australia in 2009 (Teague et al., 2010). Also, rapid economic development may increase the risks of climate-related health issues. For instance, changes in Tibet Autonomous Region, China, including new roads and substantial in-migration may explain (along with above-average warming) the appearance and establishment in Lhasa of *Culex pipiens*, a mosquito capable of transmitting the West Nile virus (Liu et al., 2013b).

A review of global trends in tropical cyclones 1970–2009 found that mortality risk at country-level depended most strongly on three factors: storm intensity, quality of governance, and levels of poverty (Peduzzi et al., 2012). Individuals and households most vulnerable to climate hazards tend to be those with relatively low socioeconomic status (Friel et al., 2008). A study of the impacts of flooding in Bangladesh found that household risk reduced with increases in both average income and number of income sources. Poorer households were not only more severely affected by flooding, but they also took preventive action less often and received assistance after flooding less frequently than did more affluent households (Brouwer et al., 2007).

In many countries, race and ethnicity are powerful markers of health status and social disadvantage. Black Americans have been reported to be more vulnerable to heat-related deaths than other racial groups in the USA (Basu and Ostro, 2008). This may be due to a higher prevalence of chronic conditions such as overweight and diabetes (Lutsey et al., 2010), financial circumstances (e.g., lower incomes may restrict access to air conditioning during heat-waves; Ostro et al., 2010), or community-level characteristics such as higher local crime rates or disrupted social networks (Browning et al., 2006). Indigenous peoples who depend heavily on local resources, and live in parts of the world where the climate is changing quickly, are generally at greater risk of economic losses and poor health. Studies of the Inuit people, for example, show that rapid warming of the Canadian Arctic is jeopardizing hunting and many other day-to-day activities, with implications for livelihoods and well-being (Ford, 2009).

11.3.5. Public Health and Other Infrastructure

Populations that do not have access to good quality health care and essential public health services are more likely to be adversely affected by climate variability and climate change (Frumkin and McMichael, 2008). Harsh economic conditions in Europe since 2008 led to cutbacks in health services in some countries, followed by a resurgence of climate-sensitive infectious diseases including malaria (Karanikolos et al., 2013). The condition of the physical infrastructure that supports human settlements also influences health risks (this includes supply of power, provision of water for drinking and washing, waste management, and sanitation; see Chapter 8). In Cuba, a country with a well-developed public health system, dengue fever has been a persistent problem in the larger cities, due in part to the lack of a constant supply of drinking water in many neighborhoods (leading to people storing water in containers that are suitable breeding sites for the disease vector *Aedes aegypti*; Bulto et al., 2006). In New York, daily mortality spiked after a city-wide power failure in August 2003, due in part to increased exposure to heat (Anderson and Bell, 2012).

11.3.6. Projections for Vulnerability

Population growth is linked to climate change vulnerability. If nothing else changes, increasing numbers of people in locations that are already resource poor and are affected by climate risks will magnify harmful impacts. Virtually all the projected growth in populations will occur in urban agglomerations, mostly in large, low latitude hot countries in which a high proportion of the workforce is deployed outdoors with little protection from heat. About 150 million people currently live in cities affected by chronic water shortages and by 2050, unless there are rapid improvements in urban environments, the number will rise to almost a billion (McDonald et al., 2011). Under a "business as usual" scenario

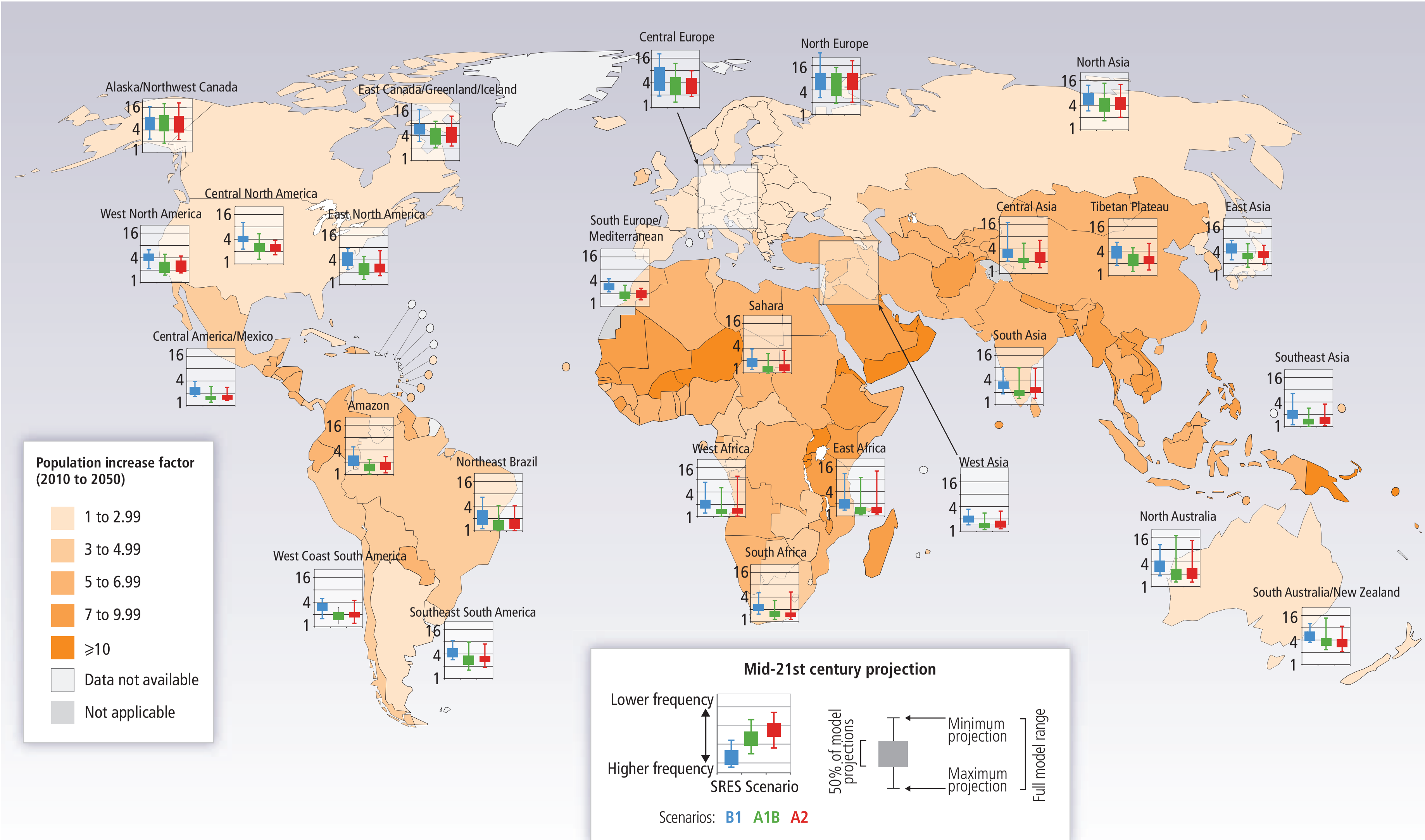

Figure 11-2 | Increasingly frequent heat extremes will combine with rapidly growing numbers of older people living in cities—who are particularly vulnerable to extreme heat. Countries are shaded according to the expected proportional increase in urban populations aged over 65 by the year 2050. Bar graphs show how frequently the maximum daily temperature that would have occurred only once in 20 years in the late 20th century is expected to occur in the mid-21st century, with lower numbers indicating more frequent events. Results are shown for three different Special Report on Emission Scenarios (SRES) scenarios (blue = B1; green = A1B, red = A2), as described in the IPCC Special Report on Emissions Scenarios, and based on 12 global climate models participating in the third phase of the Coupled Model Intercomparison Project (CMIP3). Colored boxes show the range in which 50% of the model projections are contained, and whiskers show the maximum and minimum projections from all models (WHO and WMO, 2012).

with mid-range population growth, the Organisation for Economic Co-operation and Development (OECD) projects that about 1.4 billion people will be without access to basic sanitation in 2050 (OECD, 2012). The age structure of the population also has implications for vulnerability (see Figure 11-2). The proportion aged over 60, worldwide, is projected to increase from about 10% presently to about 32% by the end of the century (Lutz et al., 2008). The prevalence of overweight and obesity, which is associated with relatively poor heat tolerance, has increased almost everywhere in the last 20 years, and in many countries the trend continues upwards (Finucane et al., 2011). It has been pointed out that the Sahel region of Africa may be particularly vulnerable to climate change because it already suffers so much stress from population pressure, chronic drought, and governmental instability (Diffenbaugh and Giorgi, 2012; Potts and Henderson, 2012).

Future trends in social and economic development are critically important to vulnerability. For instance, countries with a higher Human Development Index (HDI)—a composite of life expectancy, education, literacy, and gross domestic product (GDP) per capita—are less affected by the floods, droughts, and cyclones that take place (Patt et al., 2010). Therefore policies that boost health, education, and economic development should reduce future vulnerability. Overall, there have been substantial improvements in HDI in the last 30 years, but this has been accompanied by increasing inequalities between and within countries, and has come at the cost of high consumption of environmental resources (UNDP, 2011).

11.4. Direct Impacts of Climate and Weather on Health

11.4.1. Heat- and Cold-Related Impacts

Although there is ample evidence of the effects of weather and climate on health, there are few studies of the impacts of climate change itself. (An example: Bennett et al. (2013) reported that the ratio of summer to winter deaths in Australia increased between 1968 and 2010, in association with rising annual average temperatures.) The issue is scale, as climate change is defined in decades. Robust studies require not only extremely long-term data series on climate and disease rates, but also information on other established or potential causative factors, coupled with statistical analysis to apportion changes in health states to the various contributing factors. Wherever risks are identified, health agencies are mandated to intervene immediately, biasing long-term analyses.

Nevertheless, the connection between weather and health impacts is often sufficiently direct to permit strong inferences about cause and effect (Sauerborn and Ebi, 2012). Most notably, the association between hot days (commonly defined in terms of the percentiles of daily maximum temperature for a specified location) and increases in mortality is very robust (Honda et al., 2013). The IPCC Special Report on Extreme Events (SREX) concludes that it is *very likely* that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights, at the global scale. If there has been an increase in daily maximum temperatures, then it follows, in our view, that the number of heat-related deaths is *likely* to have also increased. For example, Christidis et al. (2012) concluded that it is "extremely likely (probability greater than 95%)" that anthropogenic climate change at least quadrupled the risk of extreme summer heat events in Europe in the decade 1999–2008. The 2003 heat wave was one such record event; therefore, the probability that particular heat wave can be attributed to climate change is 75% or more, and on this basis it is *likely* the excess mortality attributed to the heat wave (about 15,000 deaths in France alone (Fouillet et al., 2008)) was caused by anthropogenic climate change.

The rise in minimum temperatures may have contributed to a decline in deaths associated with cold spells; however, the influence of seasonal factors other than temperature on winter mortality suggests that the impacts on health of more frequent heat extremes greatly outweigh benefits of fewer cold days (Kinney et al., 2012; Ebi and Mills, 2013). Quantification, globally, remains highly uncertain, as there are few studies of the large developing country populations in the tropics, and these point to effects of heat, but not cold, on mortality (Hajat et al., 2010). There is also significant uncertainty over the degree of physiological, social, or technological adaptation to increasing heat over long time periods.

11.4.1.1. Mechanisms

The basic processes of human thermoregulation are well understood. If the body temperature rises above 38°C ("heat exhaustion"), physical and cognitive functions are impaired; above 40.6°C ("heat stroke"), risks of organ damage, loss of consciousness, and death increase sharply. Detailed exposure-response relationships were described long ago (Wyndham, 1969), but the relationships in different community settings and for different age/sex groups are not yet well established. The early studies are supported by more recent experimental and field studies (Ramsey and Bernard, 2000; Parsons, 2003) and meta-analysis (Bouchama et al., 2007) that show significant effects of heat stress as body temperatures exceed 40°C, and heightened vulnerability in individuals with preexisting disease.

At high temperatures, displacement of blood to the surface of the body may lead to circulatory collapse. Indoor thermal conditions, including ventilation, humidity, radiation from walls or ceiling, and the presence or absence of air conditioning, are important in determining whether adverse events occur, but these variables are seldom well-measured in epidemiological studies (Anderson et al., 2012). Biological mechanisms are less evident for other causes of death, such as suicide, that are sometimes related to high temperature (Page et al., 2007; Kim et al., 2011; Likhvar et al., 2011).

Heat waves refer to a run of hot days; precisely how many days, and how high the temperatures must rise, are defined variously (Kinney et al., 2008). Some investigators have reported that mortality increases more during heat waves than would be anticipated solely on the basis of the short-term temperature mortality relationship (D'Ippoliti et al., 2010; Anderson and Bell, 2011), although the added effect is relatively small in some series, and most evident with prolonged heat waves (Gasparrini and Armstrong, 2011). Because heat waves are relatively infrequent compared with the total number of days with temperatures greater than the optimum for that location, the effects of heat waves are only a fraction of the total impact of heat on health. Some studies have shown larger effects of heat and heat waves earlier in the hot season (Anderson and Bell, 2011; Rocklov et al., 2011). This may be testament to the importance of acclimatization and adaptive measures, or may result from a large group in the population that is more susceptible to heat early in the season (Rocklov et al., 2009, 2011).

The extreme heat wave in Europe in 2003 led to numerous epidemiological studies. Reports from France (Fouillet et al., 2008) concluded that most of the extra deaths occurred in elderly people (80% of those who died were older than 75 years). Questions were raised at the time as to why this event had such a devastating effect (Kosatsky, 2005). It is still not clear, but one contributing factor may have been the relatively mild influenza season the year before. Recent studies have found that when the previous year's winter mortality is low, the effect of summer heat is increased (Rocklov and Forsberg, 2009; Ha et al., 2011) because mild winters may leave a higher proportion of vulnerable people (Stafoggia et al., 2009). Most studies of heat have been in high-income countries, but there has been work recently in low- and middle-income countries, suggesting heterogeneity in vulnerability by age groups and socioeconomic factors similar to that seen in higher-income settings (Bell et al., 2008b; McMichael et al., 2008; Pudpong and Hajat, 2011).

Numerous studies of temperature-related morbidity, based on hospital admissions or emergency presentations, have reported increases in events due to cardiovascular, respiratory, and kidney diseases (Hansen et al., 2008; Knowlton et al., 2009; Lin and Chan, 2009) and the impact has been related to the duration and intensity of heat (Nitschke et al., 2011).

There is evidence now that both average levels and variability in temperature are important influences on human health. The standard deviation of summer temperatures was associated with survival time in a U.S. cohort study of persons aged older than 65 years with chronic disease who were tracked from 1985 to 2006 (Zanobetti et al., 2012). Greater variability was associated with reduced survival. A study that modeled separately projected increases in temperature variability and average temperatures for six cities for 2070–2099 found that, with one exception, variability had an effect (increased deaths) over and above what was estimated from the rise in average temperatures (Gosling et al., 2009). Relevant to Section 11.5, rapid changes in temperature may also alter the balance between humans and parasites, increasing opportunities for new and resurgent diseases. The speed with which organisms adapt to changes in temperatures is, broadly speaking, a function of mass, and laboratory studies have shown that microbes respond more quickly to a highly variable climate than do their multi-cellular hosts (Raffel et al., 2012).

Health risks during heat extremes are greater in people who are physically active (e.g., manual laborers). This has importance for recreational activity outdoors and it is relevant especially to the impacts of climate change on occupational health (Kjellstrom et al., 2009a; Ebi and Mills, 2013; see also Section 11.6.2).

Heat also acts on human health through its effects, in conjunction with low rainfall, on fire risk. In Australia in 2009, record high temperatures, combined with long-term drought, caused fires of unprecedented intensity and 173 deaths from burns and injury (Teague et al., 2010). Smoke from forest fires has been linked elsewhere with increased mortality and morbidity (Analitis et al., 2012; see Section 11.5.3.2).

11.4.1.2. Near-Term Future

The climate change scenarios modeled by WGI AR5 project rising temperatures and an increase in frequency and intensity of heat waves (Section 2.6.1; Chapter 1) in the near-term future, defined as roughly midway through the 21st century, or the era of climate responsibility (see SPM). It is uncertain how much acclimatization may mitigate the effects on human health (Wilkinson et al., 2007a; Bi and Parton, 2008; Baccini et al., 2011; Hanna et al., 2011; Maloney and Forbes, 2011; Peng et al., 2011; Honda et al., 2013). In New York, it was estimated that acclimatization may reduce the impact of added summer heat in the 2050s by roughly a quarter (Knowlton et al., 2007). In Australia, the number of "dangerously hot" days, when core body temperatures may increase by ≥2°C and outdoor activity is hazardous, is projected to rise from the current 4 to 6 days per year to 33 to 45 days per year by 2070 (with SRES A1FI) for non-acclimatized people. Among acclimatized people, an increase from 1 to 5 days per year to 5 to 14 days per year is expected (Hanna et al., 2011).

For reasons given above, it is not clear whether winter mortality will decrease in a warmer, but more variable, climate (Kinney et al., 2012; Ebi and Mills, 2013). Overall, we conclude that the increase in heat-related mortality by mid-century will outweigh gains due to fewer cold periods, especially in tropical developing countries with limited adaptive capacities and large exposed populations (Wilkinson et al., 2007b). A similar pattern has been projected for temperate zones. A study of three Quebec cities, based on SRES A2 and B2, extended to 2099, showed an increase in summer mortality that clearly outweighed a small reduction in autumn deaths, and only slight variations in winter and spring (Doyon et al., 2008). Another study in Brisbane, Australia, using years of life lost as the outcome, found the gains associated with fewer cold days were less than the losses caused by more hot days, when warming exceeded 2°C (Huang et al., 2012).

11.4.2. Floods and Storms

Floods are the most frequently occurring type of natural disaster (Guha-Sapir et al., 2011). In 2011, 6 of the 10 biggest natural disasters were flood events, when considered in terms of both number affected (112 million people) and number of deaths (3140 people) (Guha-Sapir et al., 2011). Globally, the frequency of river flood events has been increasing, as well as economic losses, due to the expansion of population and property in flood plains (Chapter 18). There is little information on health trends attributable to flooding, except for mortality and there are large differences in mortality risk between countries (UNISDR, 2011). Mortality from flooding and storm events is generally declining, but there is good evidence that mortality risks first increase with economic development before declining (De Haen and Hemrich, 2007; Kellenberg and Mobarak, 2008; Patt et al., 2010). For instance, migration to slums in coastal cities may increase population exposure at a greater pace than can be compensated for by mitigation measures (see Chapter 10 on urban risks). Severe damaging floods in Australia in 2010–2011 and in the northeastern USA in 2012 indicate that high-income countries may still be affected (Guha-Sapir et al., 2011).

11.4.2.1. Mechanisms

Flooding and windstorms adversely affect health through drowning, injuries, hypothermia, and infectious diseases (e.g., diarrheal disease, leptospirosis, vector-borne disease, cholera; Schnitzler et al., 2007; Jakubicka et al., 2010). Since AR4, more evidence has emerged on the long-term (months to years) implications of flooding for health. Flooding and storms may have profound effects on peoples' mental health (Neria, 2012). The prevalence of mental health symptoms (psychological distress, anxiety, and depression) was two to five times higher among individuals who reported flood water in the home compared to non-flooded individuals (2007 flood in England and Wales; Paranjothy et al., 2011). In the USA, signs of hurricane-related mental illness were observed in a follow-up of New Orleans' residents almost 2 years after Hurricane Katrina (Kessler et al., 2008). The attribution of deaths to flood events is complex; most reports of flood deaths include only immediate traumatic deaths, which means that the total mortality burden is under-reported (Health Protection Agency, 2012). There is some uncertainty as to whether flood events are associated with a longer-term (6 to 12 months) effect on mortality in the flooded population. No persisting effects were observed in a study in England and Wales (Milojevic et al., 2011), but longer-term increases in mortality were found in a rural population in Bangladesh (Milojevic et al., 2012).

11.4.2.2. Near-Term Future

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Under most climate change scenarios, it is expected that more frequent intense rainfall events will occur in most parts of the world in the future (IPCC, 2012). If this happens, floods in small catchments will be more frequent, but the consequence is uncertain in larger catchments (see Chapter 3). In terms of exposure, it is expected that more people will be exposed to floods in Asia, Africa, and Central and South America (Chapter 3). Also, increases in intense tropical cyclones are *likely* in the late 21st century (WGI AR5 Table SPM.1). It has been estimated conservatively that around 2.8 billion people were affected by floods between 1980 and 2009, with more than 500,000 deaths (Doocy et al., 2013). On this basis we conclude it is *very likely* that health losses caused by storms and floods will increase this century if no adaptation measures are taken. What is not clear is how much of this projected increase can be attributed to climate change. Dasgupta et al. (2009) developed a spatially explicit mortality model for 84 developing countries and 577 coastal cities. They modeled 1-in-100 year storm-surge events, and assessed future impacts under climate change, accounting for sea level rise and a 10% increase in event intensity. In the 84 developing countries, an additional 52 million people and 30,000 km^2 of land were projected to be affected by 2100.

11.4.3. Ultraviolet Radiation

Ambient ultraviolet (UV) levels and maximum summertime day temperatures are related to the prevalence of non-melanoma skin cancers and cataracts in the eye. In one study in the USA, the number of cases of squamous cell carcinoma was 5.5% higher for every 1°C increment in average temperatures, and basal cell carcinoma was 2.9% more common with every 1°C increase. These values correspond to an increase in the effective UV dose of 2% for each 1°C (van der Leun et al., 2008). However, exposure to the sun has beneficial effects on synthesis of vitamin D, with important consequences for health. Accordingly the balance of gains and losses due to increased UV exposures vary with location, intensity of exposure, and other factors (such as diet) that influence vitamin D levels (Lucas et al., 2013). Studies of stratospheric ozone recovery and climate change project that ultraviolet radiation levels at the Earth's surface will generally return to pre-1980 levels by mid-century, and may diminish further by 2100, although there is high uncertainty around the projections (Correa et al., 2013). On the other hand, higher temperatures in countries with temperate climates may result in an increase in the time which people spend outdoors (Bélanger et al., 2009) and lead to additional UV-induced adverse effects.

11.5. Ecosystem-Mediated Impacts of Climate Change on Health Outcomes

11.5.1. Vector-Borne and Other Infectious Diseases

Vector-borne diseases (VBDs) refer most commonly to infections transmitted by the bite of blood-sucking arthropods such as mosquitoes or ticks. These are some of the best-studied diseases associated with climate change, due to their widespread occurrence and sensitivity to climatic factors (Bangs et al., 2006; Bi et al., 2007; Halide and Ridd, 2008; Wu et al., 2009). Table 11-1 summarizes what is known about the influence of weather and climate on selected VBDs.

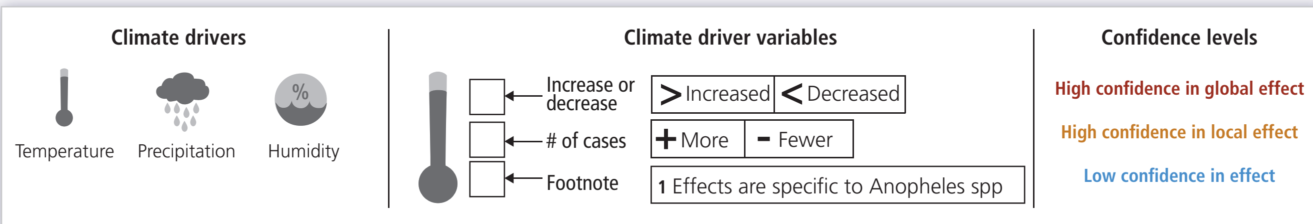
11.5.1.1. Malaria

Malaria is mainly caused by five distinct species of plasmodium parasite (*Plasmodium falciparum*, *Plasmodium vivax*, *Plasmodium malariae*, *Plasmodium ovale*, *Plasmodium knowlesi*), transmitted by Anopheline mosquitoes between individuals. In 2010 there were an estimated 216 million episodes of malaria worldwide, mostly among children younger than 5 years in the African Region (WHO, 2010). The number of global malaria deaths was estimated to be 1,238,000 in 2010 (Murray et al., 2012). Worldwide, there have been significant advances made in malaria control in the last 20 years (Feachem et al., 2010).

The influence of temperature on malaria development appears to be nonlinear, and is vector specific (Alonso et al., 2011). Increased variations in temperature, when the maximum is close to the upper limit for vector and pathogen, tend to reduce transmission, while increased variations of mean daily temperature near the minimum boundary increase transmission (Paaijmans et al., 2010). Analysis of environmental factors associated with the malaria vectors *Anopheles gambiae* and *A. funestus* in Kenya found that abundance, distribution, and disease transmission are affected in different ways by precipitation and temperature (Kelly-Hope et al., 2009). There are lag times according to the lifecycle of the vector and the parasite: a study in central China reported that malaria incidence was related to the average monthly temperature, the average

Table 11-1 | The association between different climatic drivers and the global prevalence and geographic distribution of selected vector-borne diseases observed over the period 2008-2012. Among the vector-borne diseases shown here, only dengue fever was associated with climate variables at both the global and local levels (*high confidence*), while malaria and hemorrhagic fever with renal syndrome showed a positive association at the local level (*high confidence*).

Disease	Area	Cases per year	Climate sensitivity and confidence in climate effect	Key references
Mosquito-borne diseases				
Malaria	Mainly Africa, SE Asia	About 220 million	Temperature > +− 1; Precipitation > +− 1; Precipitation < −; Humidity > +−	WHO (2008); Kelly-Hope et al. (2009); Alonso et al. (2011); Omumbo et al. (2011)
Dengue	100 countries, esp. Asia Pacific	About 50 million	Temperature > +; Precipitation > +; Temperature < −; Precipitation < −; Humidity > +−	Beebe (2009); Pham et al. (2011); Astrom et al. (2012); Earnest et al. (2012); Descloux (2012)
Tick-borne diseases				
Tick-borne encephalitis	Europe, Russian Fed., Mongolia, China	About 10,000	Temperature > +	Tokarevich et al. (2011)
Lyme	Temperate areas of Europe, Asia, North America	About 20,000 in USA	Temperature > +; Humidity > +	Bennet (2006); Ogden et al. (2008)
Other vector-borne diseases				
Hemorrhagic fever with renal syndrome (HFRS)	Global	0.15–0.2 million	Temperature > +; Precipitation > +; Humidity > +	Fang et al. (2010)
Plague	Endemic in many locations worldwide	About 40,000	Temperature > +; Precipitation > +	Stenseth et al. (2006); Ari et al. (2010); Xu et al. (2011)



temperature of the previous 2 months, and the average rainfall of the current month (Zhou et al., 2010).

More work has been done since AR4 to elucidate the role of local warming on malaria transmission in the East African highlands, but this is hampered by the lack of time series data on levels of drug resistance and intensity of vector control programs. Earlier research had failed to find a clear increase in temperatures accompanying increases in malaria transmission, but new studies with aggregated meteorological data over longer periods have confirmed increasing temperatures since 1979 (Omumbo et al., 2011; Stern et al., 2011). The strongly nonlinear response to temperature means that even modest warming may drive large increases in transmission of malaria, if conditions are otherwise suitable (Pascual et al., 2006; Alonso et al., 2011). On the other hand, at relatively high temperatures modest warming may reduce the potential of malaria transmission (Lunde et al., 2013). One review (Chaves and Koenraadt, 2010) concluded that decadal temperature changes have played a role in changing malaria incidence in East Africa. But malaria is very sensitive also to socioeconomic factors and health interventions, and the generally more conducive climate conditions have been offset by more effective disease control activities. The incidence of malaria has reduced over much of East Africa (Stern et al., 2011), although increased variability in disease rates has been observed in some high-altitude areas (Chaves et al., 2012).

At the global level, economic development and control interventions have dominated changes in the extent and endemicity of malaria over the last 100 years (Gething et al., 2010). Although modest warming has facilitated malaria transmission (Pascual et al., 2006; Alonso et al., 2011), the proportion of the world's population affected by the disease has been reduced, largely due to control of *P. vivax* malaria in moderate climates with low transmission intensity. However, the burden of disease is still high and may actually be on the increase again, in some locations (WHO, 2012). For instance, locally transmitted malaria has re-emerged in Greece in association with economic hardship and cutbacks in government spending (Danis et al., 2011; Andriopoulos et al., 2013).

11.5.1.2. Dengue Fever

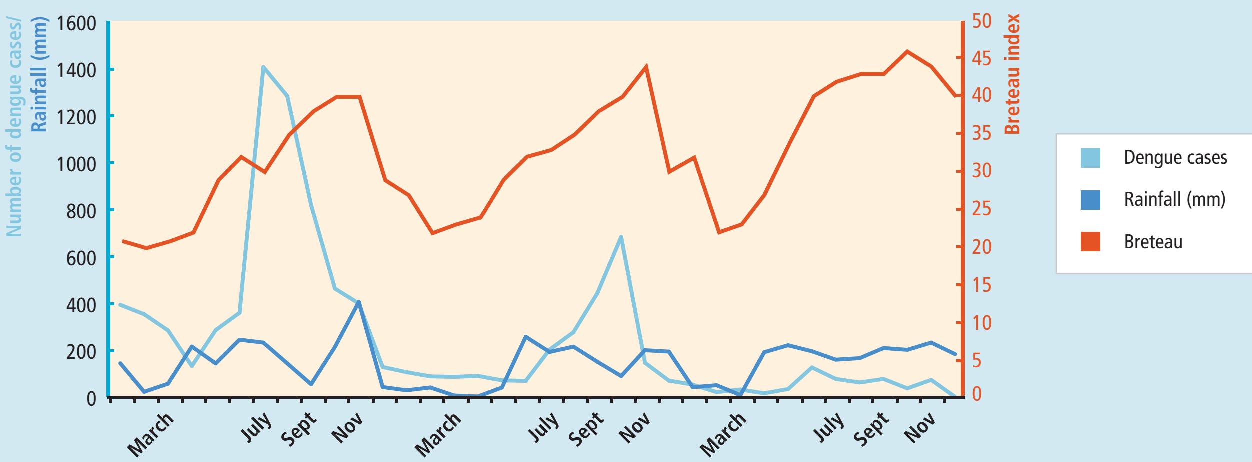
Dengue is the most rapidly spreading mosquito-borne viral disease, showing a 30-fold increase in global incidence over the past 50 years (WHO, 2013). Each year there occur about 390 million dengue infections worldwide, of which roughly 96 million manifest with symptoms (Bhatt et al., 2013). Three quarters of the people exposed to dengue are in the Asia-Pacific region, but many other regions are affected also. The first sustained transmission of dengue in Europe since the 1920s was reported in 2012 in Madeira, Portugal (Sousa et al., 2012). The disease is associated with climate on spatial (Beebe et al., 2009; Russell et al.,

Box 11-2 | Case Study: An Intervention to Control Dengue Fever

Seasonality in dengue transmission is well established in many parts of the world, and transmission occurs mostly during the wettest months of the year (Gubler and Kuno, 1997; Chadee et al., 2007). Figure 11-3 shows that about 80% of dengue fever cases in Trinidad were recorded during the wet season, a period when the *Ae. aegypti* mosquito population density was four to nine times higher than the dengue transmission threshold (Macdonald, 1956). This led to a control program that concentrated on reducing the mosquito population before the onset of the rains, by application of insecticides (temephos) into the water drums that serve as primary breeding sites of *Ae. aegypti* in the Caribbean. The one-off treatment effectively controlled the mosquito populations for almost 12 weeks after which the numbers reverted to levels observed in the untreated control areas.

Climate scenarios that extend to 2071–2100 project changes in the intensity and frequency of rainfall events in the Caribbean (Campbell et al., 2011). In these scenarios, there is greater variability in rainfall patterns during November to January, with the northern Caribbean region receiving more rainfall than in the southern Caribbean (Campbell et al., 2011). There may be water shortages during drought periods, and flooding after episodes of heavy rainfall, both of which affect the breeding habitats of *Ae. aegypti* and *Ae. albopictus*. Vector control strategies will need to be planned and managed astutely to systematically reduce mosquito populations.

(a) Rainfall, Breteau index, and Dengue cases, Trinidad (2002–2004)



(b) Efficacy of pre-seasonal treatment with temephos on *Aedes aegypti* ovitrap egg counts in Curepe (treatment) and St. Joseph (control), Trinidad (2003)

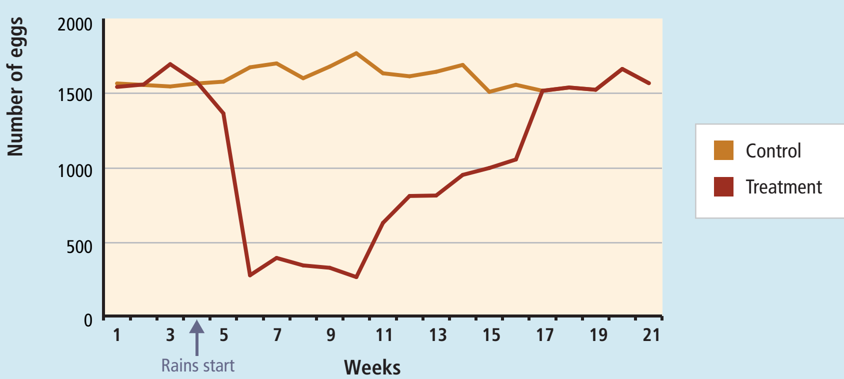


Figure 11-3 | (a) Rainfall, Breteau index (number of water containers with *Ae. aegypti* larvae per 100 houses), and dengue fever cases, Trinidad (2002–2004). Rainfall was found to be significantly correlated with an increase in the *Ae. aegypti* population and dengue fever incidence, with a clearly defined "dengue season" between June and November over two years of the study (Chadee et al., 2007). b) Efficacy of pre-seasonal treatment with temephos on *Ae. aegypti* ovitrap egg counts in Curepe (treatment) and St. Joseph (control), Trinidad (2003). Evidence of the efficacy of the pre-seasonal larval control through focal treatment of *Ae. aegypti* population is provided. Treatment at the onset of the rainy season can effectively prevent the rapid increase in *Ae. aegypti* populations and therefore suppress the onset of dengue transmission (Chadee, 2009).

2009; Li et al., 2011), temporal (Hii et al., 2009; Hsieh and Chen, 2009; Herrera-Martinez and Rodriguez-Morales, 2010; Gharbi et al., 2011; Pham et al., 2011; Descloux et al., 2012; Earnest et al., 2012) and spatiotemporal (Chowell et al., 2008, 2011; Lai, 2011) scales.

The principal vectors for dengue, Aedes aegypti and Ae. albopictus, are climate sensitive. Over the last 2 decades, climate conditions have become more suitable for albopictus in some areas (e.g., over central northwestern Europe) but less suitable elsewhere (e.g., over southern Spain) (Caminade et al., 2012). Distribution of Ae. albopictus in northwestern China is highly correlated with annual temperature and precipitation (Wu et al., 2011). Temperature, humidity, and rainfall are positively associated with dengue incidence in Guangzhou, China, and wind velocity is inversely associated with rates of the disease (Lu and Lin, 2009; Li et al., 2011). Several studies in Taiwan reported that typhoons remain an important factor affecting vector population and dengue fever (Hsieh and Chen, 2009; Lai, 2011). Typhoons result in extreme rainfall, high humidity, and water pooling, and may generate fresh mosquito breeding sites. A study in Dhaka, Bangladesh, reported increased rates of admissions to hospital due to dengue with both high and low river levels (Hashizume and Dewan, 2012). In some circumstances, it is apparent that heavy precipitation favors the spread of dengue fever, but drought can also be a cause if households store water in containers that provide suitable mosquito breeding sites (Beebe et al., 2009; Padmanabha et al., 2010).

11.5.1.3. Tick-Borne Diseases

Tick-borne encephalitis (TBE) is caused by tick-borne encephalitis virus, and is endemic in temperate regions of Europe and Asia. Lyme disease is an acute infectious disease caused by the spirochaete bacteria *Borrelia burgdorferi* and is reported in Europe, the USA, and Canada. *Borrelia* is transmitted to humans by the bite of infected ticks belonging to a few species of the genus *Ixodes* ("hard ticks"). Many studies have reported associations between climate and tick-borne diseases (Okuthe and Buyu, 2006; Lukan et al., 2010; Tokarevich et al., 2011; Andreassen et al., 2012; Estrada-Peña et al., 2012; Jaenson et al., 2012). In North America, there is good evidence of northward expansion of the distribution of the tick vector (*Ixodes scapularis*) in the period 1996–2004 based on an analysis of active and passive surveillance data (Ogden et al., 2010). However, there is no evidence so far of any associated changes in the distribution in North America of human cases of tick-borne diseases.

There was a marked rise in TBE cases from the 1970s in central and Eastern Europe. Spring-time daily maximum temperatures rose in the late 1980s, sufficient to encourage transmission of the TBE virus. For instance, in the Czech Republic, between 1970 and 2008, there were signs of lengthening transmission season and higher altitudinal range in association with warming (Kriz et al., 2012). However variations in illness rates across the region demonstrate that climate change alone cannot explain the increase. Socioeconomic changes (including changes in agriculture and recreational activities) have affected patterns of disease in Europe (Sumilo et al., 2008; Randolph, 2010). The complex ecology of tick-borne diseases such as Lyme disease and TBE make it difficult to attribute particular changes in disease frequency and distribution to specific environmental factors such as climate (Gray et al., 2009).

11.5.1.4. Other Vector-Borne Diseases

Hemorrhagic fever with renal syndrome (HFRS) is a zoonosis caused by the Hanta virus, and leads to approximately 200,000 hospitalized cases each year. The incidence of this disease has been associated with temperature, precipitation, and relative humidity (Pettersson et al., 2008; Fang et al., 2010; Liu et al., 2011). Plague, one of the oldest diseases known to humanity, persists in many parts of the world. Outbreaks have been linked to seasonal and interannual variability in climate (Stenseth et al., 2006; Nakazawa et al., 2007; Holt et al., 2009; Xu et al., 2011; MacMillan et al., 2012). Chikungunya fever is a climate-sensitive mosquito-transmitted viral disease (Anyamba et al., 2012), first identified in Africa, now present also in Asia, and the disease has recently emerged in parts of Europe (Angelini et al., 2008). The incidence in China of Japanese encephalitis, another mosquito-borne viral disease, is correlated with temperature and rainfall, especially during the warmer months of the year (Bai et al., 2013). In West Africa, outbreaks of Rift Valley Fever, an acute viral disease affecting humans and domestic animals, are linked to within-season variability in rainfall (Caminade et al., 2011).

11.5.1.5. Near-Term Future

Using the A1B climate change scenario, Béguin et al. (2011) projected the population at risk of malaria to 2030 and 2050. With GDP per capita held constant at 2010 values, the model projected 5.2 billion people at risk in 2050, out of a predicted global population of 8.5 billion. Keeping climate constant, and assuming strong economic growth allied with social development ("best case"), the model projected 1.74 billion people at risk (approximately half the present number at risk) in 2050. Factoring in climate change would increase the "best case" estimate of the number of people at risk of malaria in 2050 to 1.95 billion, which is 200 million more than if disease control efforts were not opposed by higher temperatures and shifts in rainfall patterns.

There are no recent studies that project the return of established malaria to North America or Europe, where it was once prevalent. However, suitable vectors for *P. vivax* malaria abound in these parts of the world, and recent experience in southern Europe demonstrates how rapidly the disease may reappear if health services falter (Bonovas and Nikolopoulos, 2012).

A systematic review of research on the distribution of dengue and possible influence of climate change (Van Kleef et al., 2010) concluded that the area of the planet that was climatically suitable for dengue would increase under most scenarios, but it was not possible to project the impact on disease incidence. Åström et al. (2012) estimated the population at risk out to the year 2050. The study was based on routine disease reports, surveys, population projections, estimates of GDP growth, and the A1B scenario for climate change. Assuming high GDP growth that benefits all populations, the number exposed to dengue in 2050 falls to 4.46 billion; that is, the adverse effects of climate change are balanced by the beneficial outcomes of development. This study considered only the margins of the geographic distribution of dengue (where economic development has its strongest effect) and did not examine changes in intensity of transmission in areas where the disease is already established.

Kearney (2009) used biophysical models to examine the potential extension of vector range in Australia. He predicted that climate change would increase habitat suitability throughout much of Australia. Changes in water storage as a response to a drier climate may be an indirect pathway, through which climate change affects mosquito breeding (Beebe et al., 2009).

11.5.2. Food- and Water-Borne Infections

Human exposure to climate-sensitive pathogens occurs by ingestion of contaminated water or food; incidental ingestion during swimming; or by direct contact with eyes, ears, or open wounds. Pathogens in water may be zoonotic in origin, concentrated by bivalve shellfish (e.g., oysters), or deposited on irrigated food crops. Pathogens of concern include enteric organisms that are transmitted by the fecal oral route and also bacteria and protozoa that occur naturally in aquatic systems. Climate may act directly by influencing growth, survival, persistence, transmission, or virulence of pathogens; indirect influences include climate-related perturbations in local ecosystems or the habitat of species that act as zoonotic reservoirs.

11.5.2.1. Vibrios

Vibrio is a genus of native marine bacteria that includes a number of human pathogens, most notably *V. cholerae* which causes cholera. Cholera may be transmitted by drinking water or by environmental exposure in seawater and seafood; other *Vibrio* species are solely linked to seawater and shellfish. These include *V. parahaemolyticus* and *V. vulnificus*, with *V. alginolyticus* emerging in importance (Weis, 2011). Risk of infection is influenced by temperature, precipitation, and accompanying changes in salinity due to freshwater runoff, addition of organic carbon or other nutrients, or changes in pH. These factors all affect the spatial and temporal range of the organism and also influence exposure routes (e.g., direct contact or via seafood). In countries with endemic cholera, there appears to be a robust relationship between temperature and the disease (Islam, 2009; Paz, 2009; Reyburn et al., 2011). In addition, heavy rainfall promotes the transmission of pathogens when there is not secure disposal of fecal waste. An unequivocal positive relationship between *Vibrio* numbers and sea surface temperature in the North Sea has been established by DNA analyses of formalin-fixed samples collected over a 44-year period (Vezzulli et al., 2012). Cholera outbreaks have been linked to variations in temperature and rainfall, and other variables including sea and river levels, sea chlorophyll and cyanobacteria contents, and Indian Ocean Dipole (IOD) and El Niño-Southern Oscillation (ENSO) events (de Magny et al., 2008; Hashizume, 2008; Bompangue et al., 2011; Reyburn et al., 2011; Rinaldo et al., 2012).

11.5.2.2. Other Parasites, Bacteria, and Viruses

Rates of diarrhea have been associated with high temperatures (Kolstad and Johansson, 2011). Mostly, however, neither the specific causes of the diarrheal illness are known, nor the mechanism for the association with temperature. Exceptions include *Salmonella* and *Campylobacter*, among the most common zoonotic food- and water-borne bacterial pathogens worldwide, which both show distinct seasonality in infection and higher disease rates at warmer temperatures. The association between climate (especially temperature) and non-outbreak ("sporadic") cases of salmonellosis may, in part, explain seasonal and latitudinal trends in diarrhea (Lake, 2009).

Among the enteric viruses, there are distinct seasonal patterns in infection that can be related indirectly to temperature. Enterovirus infections in the USA peak in summer and fall months (Khetsuriani et al., 2006). After controlling for seasonality and interannual variations, hand, foot, and mouth disease (caused by coxsackievirus A16 and enterovirus 71) shows a linear relationship with temperature in Singapore, with a rapid rise in incidence when the temperature exceeds 32°C (Hii et al., 2011). However, it is not clear what the underlying driver is and if temperature is confounded by other seasonal factors.

Temperature is directly linked with risk of enteric disease in Arctic communities, as melt of the permafrost hastens transport of sewage (which is often captured in shallow lagoons) into groundwater, drinking water sources, or other surface waters (Martin et al., 2007). In addition, thawing may damage drinking water intake systems (for those communities with such infrastructure) (Hess, 2008).

Rainfall has also been associated with enteric infections. Bacterial pathogens are more likely to grow on produce crops (e.g., lettuce) in simulations of warmer conditions (Liu et al., 2013a), and become attached to leafy crops under conditions of both flooding and drought (Ge et al., 2012). This latter pattern is reflected in patterns of illness (Bandyopadhyay et al., 2012). Higher concentrations of enteric viruses have been reported frequently in drinking water and recreational water following heavy rainfall (Delpla et al., 2009).

Worldwide, rotavirus infections caused about 450,000 deaths in children younger than 5 years old in 2008 (Tate et al., 2012). There are seasonal peaks in the number of cases in temperate and subtropical regions but less distinct patterns are seen within 10° latitude of the equator (Cook et al., 1990). Variations in the timing of peak outbreaks between countries or regions (Turcios et al., 2006; Atchison et al., 2010) and variations with time in the same country (Dey et al., 2010) have been attributed to fluctuations in the number and seasonality of births (Pitzer et al., 2009, 2011). While vaccination against rotavirus is expected to reduce the total burden of disease, it may also increase seasonal variation (Tate et al., 2009; Pitzer et al., 2011).

Harmful algal blooms can be formed by (1) dinoflagellates that cause outbreaks of paralytic shellfish poisoning, ciguatera fish poisoning, and neurotoxic shellfish poisoning; (2) cyanobacteria that produce toxins causing liver, neurological, digestive, and skin diseases; and (3) diatoms that can produce domoic acid, a potent neurotoxin that is bioaccumulated in shellfish and finfish (Erdner et al., 2008). Increasing temperatures promote bloom formation in both freshwater (Paerl et al., 2011) and marine environments (Marques et al., 2010; see Chapter 5). Increasing temperature favored growth of toxic over non-toxic strains of *Microcystis* in lakes in the USA (Davis et al., 2009). Projections of toxin-producing blooms in Puget Sound using an A1B scenario suggest that by the end of the century the "at risk" period may begin 2 months earlier and last up to 1 month longer than at present (Moore et al., 2011).

11.5.2.3. Near-Term Future

Kolstad and Johansson (2011) projected an increase of 8 to 11% in the risk of diarrhea in the tropics and subtropics in 2039 due to climate change, using the A1B scenario and 19 coupled atmosphere-ocean climate models from CMIP3. This study did not account for future changes in economic growth and social development. Application of down-scaled climate change models showed that overflows of sewage into Chicago's watersheds would increase by 50 to 120% by 2100, as a result of more frequent and intense rainfall (Patz et al., 2008). In Botswana, if hot, dry conditions begin earlier in the year, and are prolonged, as projected by down-scaled climate scenarios, the present dry season peak in diarrheal disease may be amplified (Alexander et al., 2013). However, the same analysis projected that incidence of diarrheal disease in the wet season would decline. Zhou et al. (2008) studied the effect of climate on transmission of schistosomiasis due to *S. japonicum* in China. They concluded that an additional 784,000 km^2 would become suitable for schistosomiasis transmission in China by 2050, as the mid-winter freezing line moves northward (Figure 11-4).

Mangal et al. (2008) constructed a mechanistic model of the transmission cycle of another species, *S. mansoni*, and reported a peak in the worm burden in humans at an ambient temperature of 30°C, falling sharply as temperature rises to 35°C. The authors attribute this to the increasing mortality of both the snails and the water-borne intermediate forms of the parasite, and noted that worm burden is not directly linked to the prevalence of schistosomiasis.

11.5.3. Air Quality

Nearly all the non-CO_2 climate-altering pollutants (see WGI AR5 Chapters 7 and 8) are health damaging, either directly or by contributing to secondary pollutants in the atmosphere. Thus, like the ocean acidification

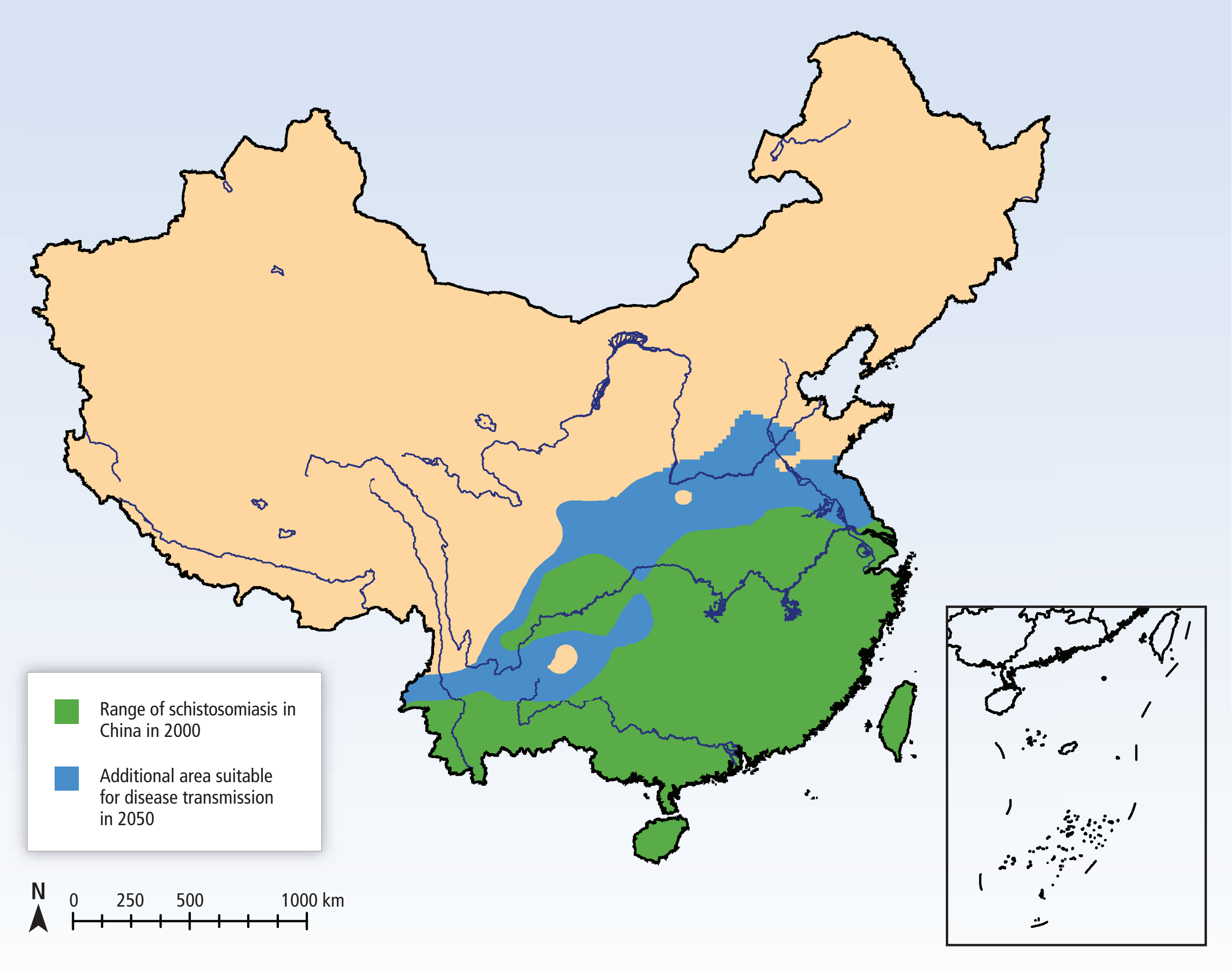


Figure 11-4 | Effect of rising temperatures on the area in which transmission of Schistosomiasis japonica may occur. Green area denotes the range of schistosomiasis in China in 2000. The blue area shows the additional area suitable for disease transmission in 2050. Based on a biology-driven model including parasite (*Schistosoma japonicum*) and snail intermediate host (*Oncomelania hupensis*) and assuming average temperatures in China in mid-winter (January) increase by 1.6°C in 2050, compared with 2000 (adapted from Zhou et al., 2008).

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Box 11-3 | Health and Economic Impacts of Climate-Altering Pollutants Other than CO_2

Although other estimates of the global health impacts of human exposures to particle and ozone pollution have been published in recent years (e.g., UNEP, 2011), the most comprehensive was the Comparative Risk Assessment carried out as part of the 2010 Global Burden of Disease Project (Lim et al., 2012). It found that the combined health impact of the household exposures to particle air pollution from poor combustion of solid cooking fuels, plus general ambient pollution, was about 6.8 million premature deaths annually, with about 5% overlapping, that is, coming from the contribution to general ambient pollution of household fuels. It also found that about 150,000 premature deaths could be attributed to ambient ozone pollution. Put into terms of disability-adjusted life years (DALYs), particle air pollution was responsible for about 190 million lost DALYs in 2010, or about 7.6% of all DALYs lost. This burden puts particle air pollution among the largest risk factors globally, far higher than any other environmental risk and rivaling or exceeding all of the five dozen risk factors examined, including malnutrition, smoking, high blood pressure, and alcohol.

The economic impact of this burden is difficult to assess as evaluation methods vary dramatically in the literature. Most in the health field prefer to consider some version of a lost healthy life year as the best metric although the economics literature often uses willingness to pay for avoiding a lost life (Jamison et al., 2006). Another difficulty is that any valuation technique that weights the economic loss according to local incomes per capita will value health effects in rich countries more than in poor countries, which would seem to violate some of the premises of a global assessment; see WGIII AR5 Chapter 3 for more discussion. Here, however, we will use the mean global income per capita (approximately US$10,000 in 2010) to scope out the scale of the impact globally without attempting to be specific by country or region.

The WHO CHOICE approach for evaluating what should be spent on health interventions indicates that one annual per capita income per DALY is a reasonable upper bound (WHO, 2009a). This would imply that the total lost economic value from global climate-altering pollutants in the form of particles is roughly US$1.9 trillion, in the sense that the world ought to be willing to pay this much to reduce it. This is about 2.7% of the global economy (approximately US$70 trillion in 2010).

On the one hand, this shows that global atmospheric pollution already has a major impact on the health and economic well-being of humanity today, due mainly to the direct effects rather than those mediated through climate. If CO_2 is not controlled and climate change continues to intensify while air pollutant controls become more stringent, the climate impacts will become more prominent. The quite different time scales for the two types of impacts make comparisons difficult, however.

Air pollution reductions do not always promote the twin goals of protecting health and climate but can pose trade-offs. All particles are dangerous for health, for example, but some are cooling, such as sulfates, and some warming, such as black carbon (Smith et al., 2009). Indeed elimination of all anthropogenic particles in the atmosphere, a major success for health, would have only a minor net impact on climate (WGI AR5 Figure TS-6). As discussed in Section 11.9, there are nevertheless specific actions that will work toward both goals.

and ecosystem/agriculture fertilization impacts of CO_2, the other CAPs have non-climate-mediated impacts, particularly on health. Although not reviewed in detail in this assessment, the health impacts of non-CO_2 CAPs are substantial globally. See Box 11-3.

Although there is a large body of literature on the health effects of particulate air pollution (see Box 11-3), WGI indicates that there is little evidence that climate change, per se, will affect long-term particle levels in a consistent way (WGI AR5 Section 11.3.5 and Annex II). Thus, we focus here on chronic ozone exposures, which are found by WGI to be enhanced in some, but not all, scenarios of future climate change (WGI AR5 TS.5.4.8).

11.5.3.1. Long-Term Outdoor Ozone Exposures

Tropospheric ozone is formed through photochemical reactions that involve nitrogen oxides (NO_x), carbon monoxide (CO), methane (CH_4), and volatile organic compounds (VOCs) in the presence of sunlight and elevated temperatures (WGI AR5 Chapter 8). Therefore, if temperatures rise, many air pollution models (Ebi and McGregor, 2008; Tsai et al., 2008; Chang et al., 2010; Polvani et al., 2011) project increased ozone production especially within and surrounding urban areas (Hesterberg et al., 2009). Enhanced temperature also accelerates destruction of ozone, and the net direct impact of climate change on ozone concentrations worldwide is thought to be a reduction (WGI AR5 TS.5.4.8). Some WGI (TS.5.4.8) scenarios, however, indicate tropospheric ozone may rise from additional CH_4 emissions stimulated by climate change. Models also show that local variations can have a different sign to the global one (Selin et al., 2009).

Even small increases in atmospheric concentrations of ground-level ozone may affect health (Bell et al., 2006; Ebi and McGregor, 2008; Jerrett et al., 2009). For instance, Bell et al. (2006) found that levels that meet the USEPA 8-hour regulation (0.08 ppm over 8 hours) were associated with increased risk of premature mortality. There is a lack of association between ozone and premature mortality only at very low concentrations (from 0 to ~10 ppb) but the association becomes positive and approximately linear at higher concentrations (Bell et al., 2006; Ebi and McGregor, 2008; Jerrett et al., 2009). In an analysis of 66 U.S. cities with 18 years of follow-up (1982–2000), tropospheric ozone levels were found to be significantly associated with cardiopulmonary mortality (Smith et al., 2009). See also the global review by WHO, which includes data from developing countries (WHO, 2006).

11.5.3.2. Acute Air Pollution Episodes

Wildfires, which occur more commonly following heat waves and drought, release particulate matter and other toxic substances that may affect large numbers of people for days to months (Finlay et al., 2012; Handmer et al., 2012). During a fire near Denver (USA) in June 2009, 1-hour concentrations of particulate matter with aerodynamic diameter <10 μm (PM_{10}) and particulate matter with aerodynamic diameter <2.5 μm ($PM_{2.5}$) reached 370 μg m^{-3} and 200 μg m^{-3}, and 24-hour average concentrations reached 91 μg m^{-3} and 44 μg m^{-3} (Vedal and Dutton, 2006), compared to the 24-hour WHO Air Quality Guidelines (AQGs) for these pollutants of 50 μg m^{-3} and 25 μg m^{-3}, respectively. One study of worldwide premature mortality attributable to air pollution from forest fires estimated there were 339,000 deaths per year (range 260,000 to 600,000) (Johnston et al., 2012). The regions most affected are sub-Saharan Africa and Southeast Asia (Johnston et al., 2012). Extremely high levels of PM_{10} were observed in Moscow due to forest fires caused by a heat wave in 2010. Daily mean temperatures in Moscow exceeded the respective long-term averages by 5°C or more for 45 days. Ten new temperature records were established in July and nine in August, based on measurements since 1885, and an anti-cyclone in the Moscow region prevented dispersion of air pollutants. The highest 24-hour pollution levels recorded in Moscow during these conditions were between 430 and 900 μg m^{-3} PM_{10} most days, but occasionally reached 1500 μg m^{-3}. The highest 24-hour CO concentration was 30 mg m^{-3} compared to the WHO AQGs of 7 mg m^{-3}, and the levels of formaldehyde, ethyl benzene, benzene, toluene, and styrene were also increased (State Environmental Institution "Mosecomonitoring," 2010).

There may be an interaction of tropospheric ozone and heat waves. Dear et al. (2005) modeled the daily mortality due to heat and exposure to ozone during the European summer heat wave of 2003 and found that possibly 50% of the deaths could have been associated with ozone exposure rather than the heat itself.

11.5.3.3. Aeroallergens

Allergic diseases are common and some are climate sensitive. Warmer conditions generally favor the production and release of airborne allergens (such as fungal spores and plant pollen) and, consequently, there may be an effect on asthma and other allergic respiratory diseases such as allergic rhinitis, as well as effects on conjunctivitis and dermatitis (Beggs, 2010). Children are particularly susceptible to most allergic diseases (Schmier and Ebi, 2009). Increased release of allergens may be amplified if higher CO_2 levels stimulate plant growth. Visual monitoring and experiments have shown that increases in air temperature cause earlier flowering of prairie tallgrass (Sherry et al., 2007). Droughts and high winds may produce windborne dust and other atmospheric materials, which contain pollen and spores, and transport these allergens to new regions.

Studies have shown that increasing concentrations of grass pollen lead to more frequent ambulance calls due to asthma symptoms, with a time lag of 3 to 5 days (Heguy et al., 2008). Pollen levels have also been linked to hospital visits with rhinitis symptoms (Breton et al., 2006). A cross-sectional study in the three climatic regions of Spain documented a positive correlation between the rate of child eczema and humidity, and negative correlation between child eczema and air temperature or the number of sunshine hours (Suarez-Varela et al., 2008).

11.5.3.4. Near-Term Future

It is projected by WGI that climate change could affect future air quality, including levels of photochemical oxidants and, with much less certainty, fine particles ($PM_{2.5}$). If this occurs, there will be consequences for human health (Bell et al., 2007; Dong et al., 2011; Chang et al., 2012; Lepeule et al., 2012; Meister et al., 2012; West et al., 2013). High temperatures may also magnify the effects of ozone (Ren et al., 2008; Jackson et al., 2010). Increasing urbanization, use of solid biomass fuels, and industrial development in the absence of emission controls could also lead to increases in ozone chemical precursors (Selin et al., 2009; Wilkinson et al., 2009).

Most post-2006 studies on the projected impacts of future climate change on air pollution-related morbidity and mortality have focused on ozone in Europe, the USA, and Canada (Bell et al., 2007; Selin et al., 2009; Tagaris et al., 2009). Projections are rare for other areas of the world, notably the developing countries where air pollution is presently a serious problem and is expected to worsen unless controls are strengthened.

Higher temperatures may magnify the effects of air pollutants like ozone, although estimates of the size of this effect vary (Ren et al., 2008; Jackson et al., 2010). In general, all-cause mortality related to ozone is expected to increase in the USA and Canada (Bell et al., 2007; Tagaris et al., 2009; Jackson et al., 2010; Cheng et al., 2011). Under a scenario in which present air quality legislation is rolled out everywhere, premature deaths due to ozone would be wound back in Africa, South Asia, and East Asia. Under a maximum feasible CO_2 reduction scenario related to A2, it is projected that 460,000 premature ozone-related deaths could be avoided in 2030, mostly in South Asia (West et al., 2007a). All-cause mortality, however, is not the best metric for comparing air pollution health impacts across regions, given that background disease conditions vary so widely. HIV deaths and malaria deaths, which are prominent in sub-Saharan Africa, for example, are not expected to increase from air pollution exposures in the same way as deaths from cardiovascular disease that dominate other regions.

A study that investigated regional air quality in the USA in 2050, using a down-scaled climate model (Goddard Institute for Space Studies, Global Climate Model), concluded there would be about 4000 additional annual premature deaths due to increased exposures to $PM_{2.5}$ (Tagaris et al., 2009). Air pollutant-related mortality increases are also projected for Canada, but in this case they are largely driven by the effects of ozone (Cheng et al., 2011). On the basis of the relation of asthma to air quality in the last decade (1999–2010), Thompson et al. (2012) anticipate that the prevalence of asthma in South Africa will increase substantially by 2050. Sheffield et al. (2011), applying the SRES A2 scenario, projected a median 7.3% increase in summer ozone-related asthma emergency department visits for children (0 to 17 years) across New York City by the 2020s compared to the 1990s.

11.6. Health Impacts Heavily Mediated through Human Institutions

11.6.1. Nutrition

Nutrition is a function of agricultural production (net of post-harvest wastes and storage losses), socioeconomic factors, such as food prices and access, and human diseases, especially those that affect appetite, nutrient absorption, and catabolism (Black et al., 2008; Lloyd et al., 2011). All three may be influenced by climate but only agricultural production has been modeled in a climate impacts framework. Here we use the terms undernutrition, which is a health outcome, and undernourishment, which reflects national (post-trade) calories available for human consumption, and is expressed as estimated percent of the population receiving "insufficient" calories. We do not use the term "malnutrition," as it includes overnutrition, which is not considered here (except under co-benefits in Section 11.9). Undernutrition can be chronic, leading to stunting (low height for age), or acute, leading to wasting (low weight for height); underweight (low weight for age) is a combination of chronic and acute undernutrition.

11.6.1.1. Mechanisms

The processes through which climate change can affect human nutrition are complex (see Section 7.2.2). Higher temperatures and changes in precipitation may reduce both the quantity and quality of food harvested (e.g., Battisti and Naylor, 2009). Lobell et al. (2011b) showed for African maize that for each degree above 30°C, yields decreased by 1% under optimal rainfall conditions and by 1.7 % under drought conditions. From their systematic review of more than a thousand studies, Knox et al. (2012) drew the conclusion that "climate change is a threat to crop productivity in areas that are already food insecure." Rising temperatures may also affect food security through the impact of heat on productivity of farmers (see Section 11.6.2).

The magnitude of detected and predicted decline in land-based agricultural production due to increasing temperatures and changes in rainfall must be put in perspective to other changes, such as increase in harvests due to improved farming knowledge and technology, the amount of food fed to livestock, used for biofuels, consumed beyond baseline needs by the overnourished, or wasted in other ways (Foley et al., 2011). There is good evidence that local food price increases have negative effects on food consumption, and therefore on health (Green et al., 2013). Against this background, the global food price fluctuates, though with a recently rising trend. While the main driver is higher energy costs, amplified by speculation (Piesse and Thirtle, 2009), there is growing evidence (Auffhammer, 2011) that extreme weather events, especially floods, droughts (Williams and Funk, 2011), and heat waves, may have contributed to higher prices. All else being equal, higher prices increase the number of malnourished people. See Chapter 7 for a more detailed discussion of the impact of climate change on food production.

11.6.1.2. Near-Term Future

Since AR4 at least four studies have been published which project the effect of climate change on undernourishment and undernutrition.

Nelson et al. (2009, 2010) conducted two studies using a crop simulation model (DSSAT) and a global agricultural trade model (IMPACT 2009) to estimate crop production (with and without CO_2 enrichment), calorie availability, child underweight, and adaptation costs. The first study (Nelson et al., 2009) was carried out under the A2 emission scenario, using two General Circulation Models (GCMs): National Center for Atmospheric Research (NCAR) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) and relative to a "no climate change" future. The authors found that yields of most important crops would decline in developing countries by 2050, that per capita calorie

Table 11-2 | Number of undernourished children younger than 5 years of age (in millions) in 2000 and 2050, using the National Center for Atmospheric Research (NCAR) climate model (and the A2 scenario from AR4). Results assume no effect of heat on farmers' productivity, and no CO_2 fertilization benefits. (Adapted from Nelson et al., 2009).

Scenario		South Asia	East Asia/Pacific	Europe and Central Asia	Latin America and Caribbean	Middle East/ North Africa	Sub-Saharan Africa	All developing countries
2000		75.6	23.8	4.1	7.7	3.5	32.7	147.9
2050	No climate change	52.3	10.1	2.7	5.0	1.1	41.7	113.3
	Climate change	59.1	14.5	3.7	6.4	2.1	52.2	138.5

availability would drop below levels that applied in the year 2000, and that child underweight would be approximately 20% higher (in the absence of carbon enrichment effects). That is, about 25 million children would be affected (see Table 11-2). Of note, the underweight estimates do not account for possible improvements in socioeconomic conditions between 2000 and 2050. However, it was estimated that substantial improvements would be necessary to counteract the effects of climate change. These included a 60% increase in yield growth (all crops) over baseline, 30% faster growth in animal numbers, and a 25% increase in the rate of expansion of irrigated areas. The second study by Nelson et al. used a wider range of socioeconomic and climate scenarios but health impacts were similar to the first study. Estimates of improved socioeconomic conditions were insufficient to fully offset the potential impacts of climate change: child underweight was estimated to be approximately 10% higher with climate change compared to a future without climate change.

Lloyd et al. (2011) built a model for estimating future stunting driven by two principal inputs: estimates of undernourishment (i.e., "food-related" causes of stunting) and socioeconomic conditions (i.e., "non-food-related" causes of stunting). The former were based on calorie availability estimates from Nelson et al. (2009), and the latter on GDP per capita projections and estimates of the Gini index for income distribution. They estimated that by 2050, under A2 emissions with moderate to high economic growth and compared to a future without climate change, there may be a relative increase of severe stunting of 31 to 55% across regions of sub-Saharan Africa and 61% in South Asia. It should be noted here that severe stunting carries three to four times the mortality risk of moderate stunting. In a future without climate change, undernutrition was projected to decline, leading the authors to conclude that climate change would hold back efforts to reduce child undernutrition in the most severely affected parts of the world, even after accounting for the potential benefits of economic growth.

In addition to global studies, regional projections of the impacts of climate change on undernutrition have also been carried out since AR4. Grace et al. (2012) modeled the relationship between climate variables (temperature and precipitation), food production and availability, as well as child stunting in Kenya. The authors concluded that climate change will increase the proportion of stunted children in countries such as Kenya that are dependent on rain-fed agriculture, unless there are substantial adaptation efforts, such as investment in education and agricultural technology.

Similarly, Jankowska et al. (2012) included climate, livelihood, and health variables (stunting and underweight). The authors identified a link between type of livelihood and risk of undernutrition, and climate and stunting. Applying the model to Mali, the authors projected impacts to 2025 and estimated that nearly 6 million people may experience undernutrition due to changes in climate, livelihood, and demography; three-quarter to one million of this number will be children younger than five.

In summary, we conclude that climate change will have a substantial negative impact on (1) per capita calorie availability; (2) childhood undernutrition, particularly stunting; and (3) on undernutrition-related child deaths and DALYs lost in developing countries (*high confidence*).

11.6.2. Occupational Health

Since AR4, much has been written on the effects of heat on working people (Kjellstrom et al., 2009a; Dunne et al., 2013) and on other climate-related occupational health risks (Bennett and McMichael, 2010; Schulte and Chun, 2009).

11.6.2.1. Heat Strain and Heat Stroke

Worldwide, more than half of all non-household labor-hours occur outdoors, mainly in agriculture and construction (IFAD, 2010; ILO, 2013). Individuals who are obliged to work outside in hot conditions, without access to shade, or sufficient water, are at heightened risk of heat strain (ICD code T.67, "heat exhaustion") and heat stroke. Health risks increase with the level of physical exertion. Agricultural and construction workers in tropical developing countries are therefore among the most exposed, but heat stress is also an issue for those working indoors in environments that are not temperature-controlled, and even for some workers in high-income countries such as the USA (Luginbuhl et al., 2008; see Figure 11-5). Moreover, at higher temperatures there is potential conflict between health protection and economic productivity (Kjellstrom et al., 2011): as workers take longer rests to prevent heat stress, hourly productivity goes down (Sahu et al., 2013).

11.6.2.2. Heat Exhaustion and Work Capacity Loss

There are international standards of maximum recommended workplace heat exposure and hourly rest time (e.g., ISO, 1989; Parsons, 2003) for both acclimatized and non-acclimatized people. In hot countries during the hot season, large proportions of the workforce are affected by heat, and the economic impacts of reduced work capacity may be sufficient to jeopardize livelihoods (Lecocq and Shalizi, 2007; Kjellstrom et al., 2009a, 2011; Kjellstrom and Crowe, 2011). Kjellstrom and Crow (2011) and Dunne et al. (2013) report that loss of work productivity during the hottest and wettest seasons has already occurred, at least in Asia and Africa.

11.6.2.3. Other Occupational Health Concerns

In areas where vector-borne diseases, such as malaria and dengue fever, are common, people working in fields without effective protection may experience a higher incidence of these diseases when climatic conditions favor mosquito breeding and biting (Bennett and McMichael, 2010). Increasing heat exposure in farm fields during the middle of the day may lead to more work during dawn and dusk when some of the vectors are biting humans more actively. Exposure to heat affects psychomotor, perceptual, and cognitive performance (Hancock et al., 2007) and increases risk of injuries (Ramsey, 1995). Extreme weather events and climate-sensitive infectious diseases also pose occupational risks to health workers, which may in turn undermine health protection for the wider population (WHO, 2009b). Other mechanisms include elevated occupational exposures to toxic chemical solvents that evaporate faster at higher temperatures (Bennett and McMichael, 2010) and rising temperatures reducing sea ice and increasing risk of drowning in those engaged in traditional hunting and fishing in the Arctic (Ford et al., 2008).

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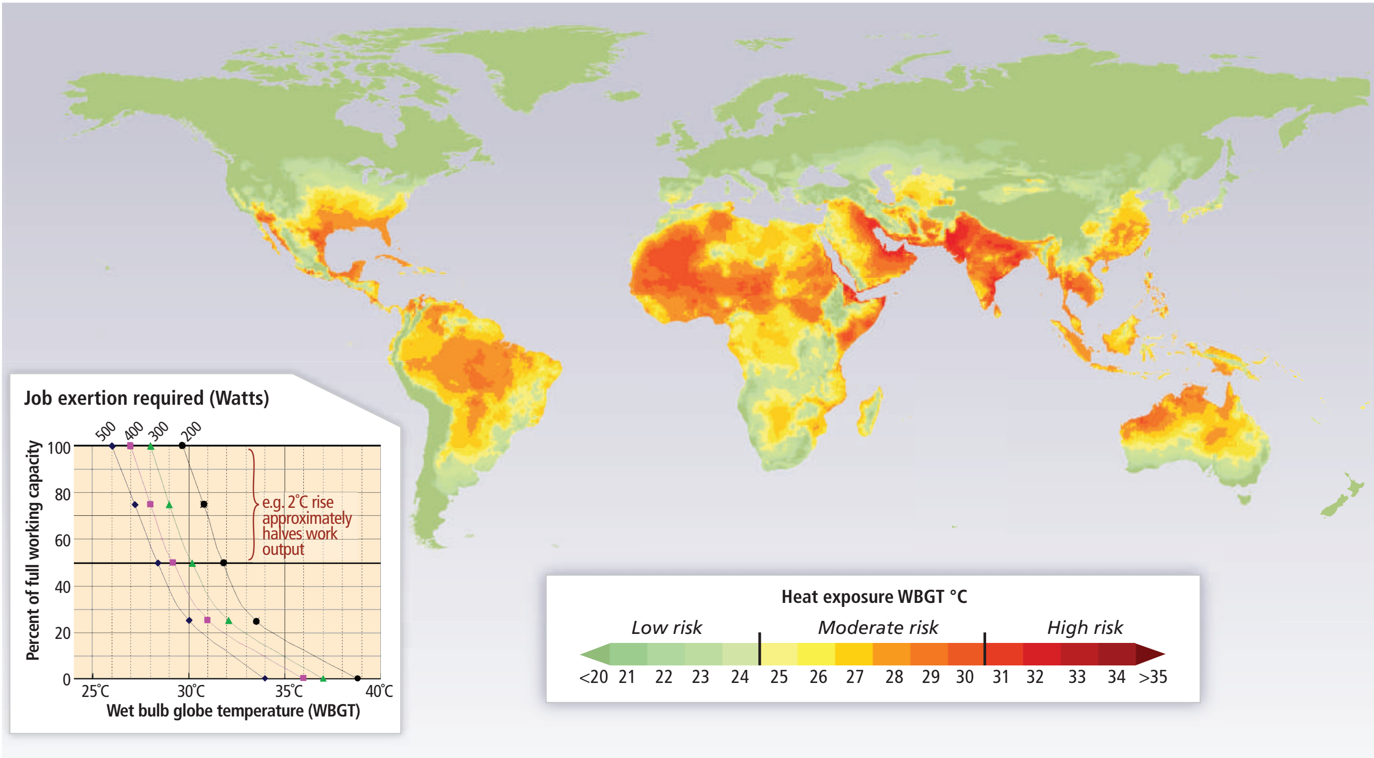

Figure 11-5 | The 1980–2009 average of the hottest months globally, measured in web bulb globe temperature (WBGT), which combines temperature, humidity, and other factors into a single index of the impact on work capacity and threat of heat exhaustion. The insert shows the International Organization for Standardization standard (ISO,1989) for heat stress in the workplace that leads to recommendations for increased rest time per hour to avoid heat exhaustion at different work levels. This is based on studies of healthy young workers and includes a margin of safety. Note that some parts of the world already exceed the level for safe work activity during the hottest month. In general, with climate change, for every 1°C that T_{max} goes up, the WBGT goes up by about 0.9°C, leading to more parts of the world being restricted for more of the year, with consequent impacts on productivity, heat exhaustion, and need for air conditioning to protect health (Lemke and Kjellstrom, 2012).

11.6.2.4. Near-Term Future

Projections have been made of the future effects of heat on work capacity (Kjellstrom et al., 2009b; Dunne et al., 2013). Temperature and humidity were both included, and the modeling took into account the changes in the workforce distribution relating to the need for physical activity. In Southeast Asia, in 2050, the model indicates that more than half the afternoon work hours will be lost due to the need for rest breaks (Kjellstrom et al., 2013). By 2100, under RCP4.5, Dunne et al. (2013) project up to a 20% loss of productivity globally. There is an unfortunate trade-off between health impact and productivity, which creates risks for poor and disenfranchised laborers working under difficult working conditions and inflexible rules (Kjellstrom et al., 2009a, 2011; Sahu et al., 2013).

11.6.3. Mental Health

Harsher weather conditions such as floods, droughts, and heat waves tend to increase the stress on all those who are already mentally ill, and may create sufficient stress for some who are not yet ill to become so (Berry et al., 2010). Manifestations of disaster-related psychiatric trauma include severe anxiety reactions (such as post-traumatic stress) and longer-term impacts such as generalized anxiety, depression, aggression, and complex psychopathology (Ahern et al., 2005; Ronan et al., 2008). For slow-developing events such as prolonged droughts, impacts include chronic psychological distress and increased incidence of suicide (Alston and Kent, 2008; Hanigan et al., 2012). Extreme weather conditions may have indirect effects on those with mental illness, through the impacts on agricultural productivity, fishing, forestry, and other economic activities. Disasters such as cyclones, heat waves, and major floods may also have destructive effects in cities. Here again, the mentally ill may be at risk: cities often feature zones of concentrated disadvantage where mental disorders are more common (Berry, 2007) and there is also higher risk of natural disasters (such as flooding).

In addition to effects of extreme weather events on mental health via the risk/disadvantage cycle, there may be a distressing sense of loss, known as "solastalgia," that people experience when their land is damaged (Albrecht et al., 2007) and they lose amenity and opportunity.

11.6.4. Violence and Conflict

Soil degradation, freshwater scarcity, population pressures, and other forces that are related to climate are all potential causes of conflict. The relationships are not straightforward, however, as many factors influence conflict and violence. The topic is reviewed closely in Chapter 12, which concludes that factors associated with risk of violent conflict, such as poverty and impaired state institutions, are sensitive to climate variability, but evidence of an effect of climate change on violence is contested. Also, it is noted that populations affected by violence are particularly vulnerable to the impacts of climate change on health and social well-being.

11.7. Adaptation to Protect Health

Climate change may threaten the progress that has been made in reducing the burden of climate-related disease and injury. The degree to which programs and measures will need modification to address additional pressures from climate change will depend on the current burden of ill health; the effectiveness of current interventions; projections of where, when, and how the health burden could change with climate change; the feasibility of implementing additional programs; other stressors that could increase or decrease resilience; and the social, economic, and political context for intervention (Ebi et al., 2006).

The scientific literature on adaptation to climate change has expanded since AR4, and there are many more national adaptation plans that include health, but investment in specific health protection activities is growing less rapidly. A review by the World Health Organization in 2012 estimated that commitments to health adaptation internationally amount to less than 1% of the annual health costs attributable to climate change in 2030 (WHO Regional Office for Europe, 2013).

The value of adaptation is demonstrated by the health impacts of recent disasters associated with extreme weather and climate events, although not necessarily attributed with confidence to climate change itself. For example, approximately 500,000 people died when Cyclone Bhola (category 3 in severity) hit East Pakistan (present day Bangladesh) in 1970 (Khan, 2008). In 1991, a cyclone of similar severity caused about 140,000 deaths. In November 2007, Cyclone Sidr (category 4) resulted in approximately 3400 deaths. The population had grown by more than 30 million in the intervening period (Mallick et al., 2005). Bangladesh achieved this remarkable reduction in mortality through effective collaborations between governmental and non-governmental organizations and local communities (Khan, 2008).

Alongside improving general disaster education (greatly assisted by rising literacy rates, especially among women), the country deployed early warning systems and built a network of cyclone shelters. Early warning systems included high-technology information systems and relatively simple measures such as training volunteers to distribute warning messages by bicycle.

Efforts to adapt to the health impacts of climate change can be categorized as incremental, transitional, and transformational actions (O'Brien et al., 2012). Incremental adaptation includes improving public health and health care services for climate-related health outcomes, without necessarily considering the possible impacts of climate change. Transitional adaptation means shifts in attitudes and perceptions, leading to initiatives such as vulnerability mapping and improved surveillance systems that specifically integrate environmental factors. Transformational adaptation (see Chapter 16), which requires fundamental changes in systems, has yet to be implemented in the health sector.

11.7.1. Improving Basic Public Health and Health Care Services

Although the short time period since health adaptation options have been implemented means evidence of effectiveness in specifically reducing climate change-related impacts is currently lacking, there is abundant evidence of steps that may be taken to improve relevant public health functions (Woodward et al., 2011). This is important because the present health status of a population may be the single most important predictor of both the future health impacts of climate change and the costs of adaptation (Pandey, 2010). Most health adaptation focuses on improvements in public health functions to reduce the current adaptation deficit, such as enhancing disease surveillance, monitoring environmental exposures, improving disaster risk management, and facilitating coordination between health and other sectors to deal with shifts in the incidence and geographic range of diseases (Woodward et al., 2011).

Examples of incremental health care interventions include introduction of vaccination programs in the USA, after which seasonal outbreaks of rotavirus, a common climate-sensitive pathogen, were delayed and diminished in magnitude (Tate et al., 2009). Post-disaster initiatives also are important. For example, an assessment of actions to improve the resilience of vulnerable populations to heat waves recommended staff planning over the summer period, cooling of health care facilities, training of staff to recognize and treat heat strain, and monitoring of those in the highest risk population groups (WHO Regional Office for Europe, 2009). Ensuring essential medical supplies for care of individuals with chronic conditions, including effective post-disaster distribution, would increase the ability of communities to manage large-scale floods and storms. In Benin, one measure proposed as part of the national response to sea level rise and flooding is expanded health insurance arrangements, so that diseases such as malaria and enteric infections can be treated promptly and effectively (Dossou and Glehouenou-Dossou, 2007).

11.7.2. Health Adaptation Policies and Measures

Transitional adaptation moves beyond focusing on reducing the current adaptation deficit to considerations of how a changing climate could alter health burdens and the effectiveness of interventions (Frumkin et al., 2008). For example, maintaining and improving food safety in the face of rising temperatures and rainfall extremes depends on effective interactions between human health and veterinary authorities, integrated monitoring of food-borne and animal diseases, and improved methods to detect pathogens and contaminants in food (Tirado et al., 2010). Indicators of community functioning and connectedness also are relevant because communities with high levels of social capital tend to be more successful in disseminating health and related messages, providing support to those in need (Frumkin et al., 2008).

11.7.2.1. Vulnerability Mapping

Vulnerability mapping is being increasingly used to better understand current and possible future risks related to climate change. For example, Reid et al. (2009) mapped community determinants of heat vulnerability in the USA. The four factors explaining most of the variance were a combination of social and environmental factors, social isolation, prevalence of air conditioning, and the proportion of the population who were elderly or diabetic. Remote-sensing technologies are now sufficiently fine-grained to map local vulnerability. For example, these technologies can be used to map surface temperatures and urban heat island effects at the neighborhood scale, indicating where city greening and other urban cooling measures could be most effective, and alerting public health authorities to populations that may be at greatest risk of heat waves (Luber and McGeehin, 2008). In another example, spatial modeling of geo-referenced climate and environmental information was used to identify characteristics of domestic malaria transmission in 2009–2012 in Greece, to guide malaria control efforts (Sudre et al., 2013). Mapping at regional and larger scales may be useful to guide adaptation actions. In Portugal, modeling of Lyme disease indicates that future conditions will be less favorable for disease transmission in the south, but more favorable in the center and northern parts of the country (Casimiro et al., 2006). This information can be used to modify surveillance programs before disease outbreaks occur. To capture a more complete picture of vulnerability, mapping exercises also could consider climate sensitivity and adaptation capacity, such as was done in an assessment of climate change and risk of poverty in Africa (Thornton et al., 2008).

11.7.3. Early Warning Systems

Early warning systems have been developed in many areas to prevent negative health impacts through alerting public health authorities and the general public about climate-related health risks. Effective early warning systems take into consideration the range of factors that can drive risk and are developed in collaboration with end users.

Components of effective early warning systems include forecasting weather conditions associated with increased morbidity or mortality, predicting possible health outcomes, identifying triggers of effective and timely response plans that target vulnerable populations, communicating risks and prevention responses, and evaluating and revising the system to increase effectiveness in a changing climate (Lowe et al., 2011). Heat wave early warning systems are being increasingly implemented, primarily in high-income countries. Of seven studies of the effectiveness of heat wave early warning systems or heat prevention activities to reduce heat-related mortality, six reported fewer deaths during heat waves after implementation of the system (Palecki et al., 2001; Weisskopf et al., 2002; Ebi et al., 2004; Tan et al., 2007; Fouillet et al., 2008; Chau et al., 2009); only Morabito et al. (2012) was inconclusive. For example, in the summer of 2006, France experienced high temperatures with about 2000 excess deaths. This was more than 4000 fewer deaths than was anticipated on the basis of what occurred in the 2003 heat wave. A national assessment attributed the lower than expected death toll to greater public awareness of the health risks of heat, improved health care facilities, and the introduction in 2004 of a heat wave early warning system (Fouillet et al., 2008). A review of the heat wave early warning systems in the 12 European countries with such plans concluded that evaluations of the effectiveness of these systems is urgently needed to inform good practices, particularly understanding which actions increase resilience (Lowe et al., 2011).

Early warning systems have been developed also for vector-borne and food-borne infections, although evidence of their effectiveness in reducing disease burdens is limited. In Botswana, an early warning system forecasts malaria incidence up to 4 months in advance based on observed rainfall; interannual and seasonal variations in climate are associated with outbreaks of malaria in this part of Africa. Model outputs include probability distributions of disease risk and measures of the uncertainty associated with the forecasts (Thomson et al., 2006). A weather-based forecasting model for dengue, developed in Singapore, predicted epidemics 13 months ahead of the peak in new cases, which gave the national control program time to increase control measures (Hii et al., 2012). A study of campylobacteriosis in the USA developed models of monthly disease risk with a very good fit in validation data sets (R^2 up to 80%) (Weisent et al., 2010).

11.7.4. Role of Other Sectors in Health Adaptation

Other sectors—including ecosystems, water supply and sanitation, agriculture, infrastructure, energy and transportation, land use management, and others—play an important part in determining the risks of disease and injury resulting from climate change.

Within the context of the EuroHEAT project, a review of public health responses to extreme heat in Europe identified transport policies, building design, and urban land use as important elements of national and municipal heat wave and health action plans (WHO Regional Office for Europe, 2009). A study examining well-established interventions to reduce the urban heat island effect (replacing bitumen and concrete with more heat-reflective surfaces, and introducing more green spaces to the city) estimated these would reduce heat-related emergency calls for medical assistance by almost 50% (Silva et al., 2010). Urban green spaces lower ambient temperatures, improve air quality, provide shade, and may be good for mental health (van den Berg et al., 2010). However, the extent to which changes in these factors reduce heat wave-related morbidity and mortality depend on location. A study in London, UK, found that built form and other dwelling characteristics more strongly influenced indoor temperatures during heat waves than did the urban health island effect (Oikonomou and Wilkinson, 2012).

A review of food aid programs indicates that a rapid response to the risk of child undernutrition, targeted to those in greatest need, with flexible financing and the capacity to rapidly scale up depending on need, may reduce damaging health consequences (Alderman, 2010). Community-based programs designed for other purposes can facilitate adaptation, including disaster risk management. In the Philippines, for example, interventions in low-income urban settings with the potential to reduce the harmful effects of climate extremes on health include savings schemes, small-scale loans, hygiene education, local control and maintenance of water supplies, and neighborhood level solid waste management strategies (Dodman et al., 2010). It is important to note that climate change adaptation in other sectors may influence health in a positive manner (e.g., re-vegetation of watersheds to improve water quality), or on occasion, exacerbate health risks (e.g., urban wetlands designed primarily for flood control may promote mosquito breeding) (Medlock and Vaux, 2011).

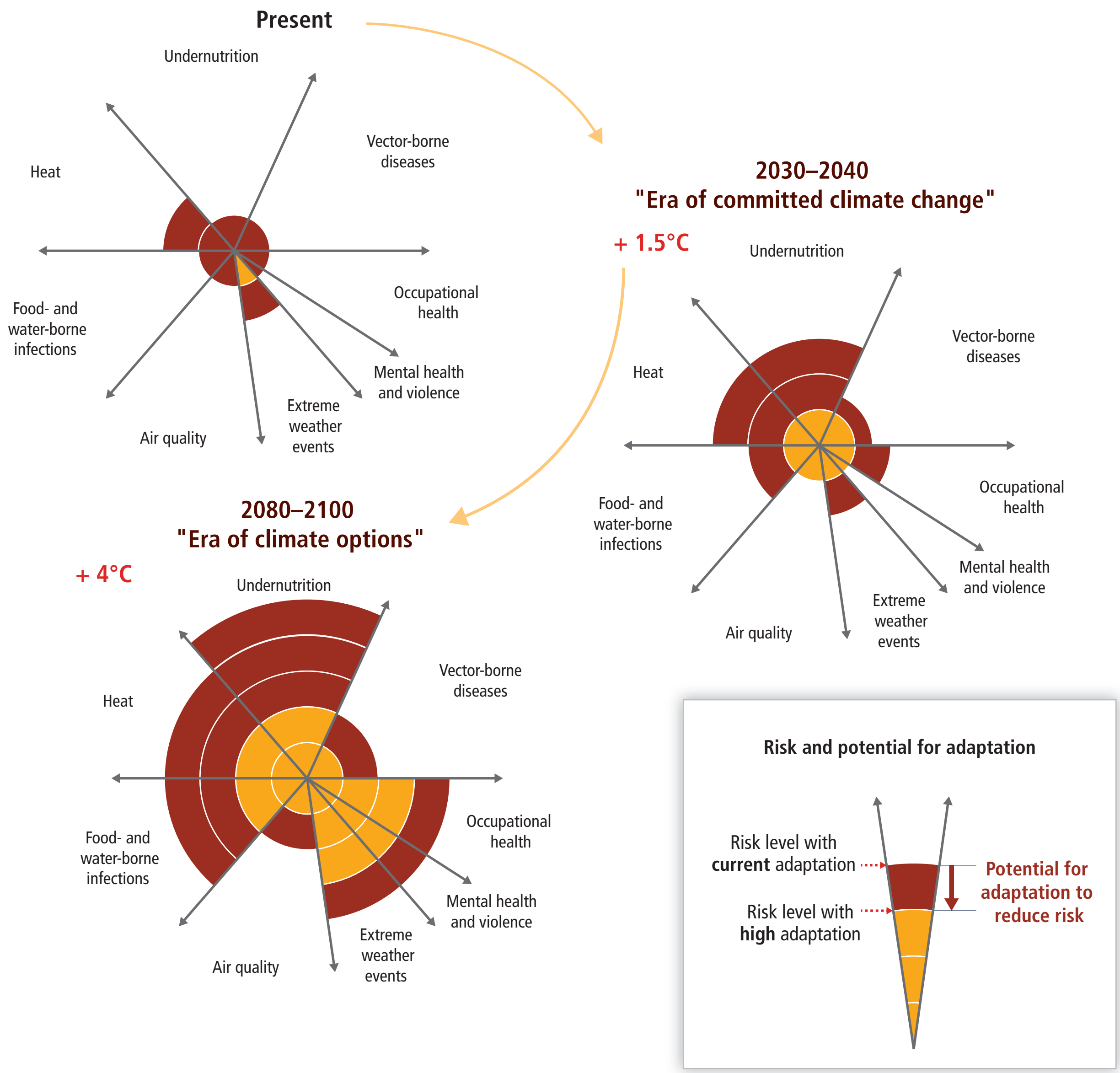

Figure 11-6 | Conceptual presentation of the health impacts from climate change and the potential for impact reduction through adaptation. Impacts are identified in eight health-related sectors based on assessment of the literature and expert judgments by authors of Chapter 11. The width of the slices indicates in a qualitative way the relative importance in terms of burden of ill health globally at present and should not be considered completely independent. Impact levels are presented for the near-term "era of committed climate change" (2030–2040), in which projected levels of global mean temperature increases do not diverge substantially across emissions scenarios. For some sectors, for example, vector-borne diseases, heat/cold stress, and agricultural production and undernutrition, there may be benefits to health in some areas, but the net impact is expected to be negative. Estimated impacts are also presented for the longer-term "era of climate options" (2080–2100), for global mean temperature increase of 4°C above preindustrial levels, which could potentially be avoided by vigorous mitigation efforts taken soon. For each timeframe, impact levels are estimated for the current state of adaptation and for a hypothetical highly adapted state, indicated by different colors.

11.8. Adaptation Limits Under High Levels of Warming

Most attempts to quantify health burdens associated with future climate change consider modest increases in global average temperature, typically less than 2°C. However, research published since AR4 raises doubt over whether it will be possible to limit global warming to 2°C above preindustrial temperatures (Rogelj et al., 2009; Anderson and Bows, 2011; PriceWaterhouseCoopers, 2012). It is therefore increasingly important to examine the likely health consequences of warming beyond 2°C, including extreme warming of 4°C to 6°C or higher. Predictions of this nature are limited by uncertainty about climatic as well as key, non-climatic determinants of health including the nature and degree of adaptation. Here, we instead focus primarily on physiological or ecological limits that constrain our ability to adapt and protect human health and wellbeing (Section 16.4.1).

It can be assumed that the increase in many important climate-related health impacts at increasingly higher levels of warming will be greater than simple linear increments; that is, that the health consequences of a 4°C temperature increase will be more than twice those of a +2°C world (see Figure 11-6). Nonlinear and threshold effects have been observed in the mortality response to extreme heat (Anderson and Bell, 2011; McMichael, 2013a), agricultural crop yields, as key determinants of childhood nutrition and development (Schlenker and Roberts, 2009; Lobell et al., 2011a), and infectious diseases (Altizer et al., 2006), for example. These are also briefly elaborated here.

11.8.1. Physiological Limits to Human Heat Tolerance

In standard (or typical) conditions, core body temperatures will reach lethal levels under sustained periods of wet-bulb temperatures above about 35°C (Sherwood and Huber, 2010). Sherwood and Huber (2010) conclude that a global mean warming of roughly 7°C above current temperatures would create small land areas where metabolic heat dissipation would become impossible. An increase of 11°C to 12°C would enlarge these zones to encompass most of the areas occupied by today's human population. This analysis is likely a conservative estimate of an absolute limit to human heat tolerance because working conditions are hazardous at lower thresholds. The U.S. military, for example, suspends all physical training and strenuous exercise when the wet-bulb globe temperature (WBGT) exceeds 32°C (Willett and Sherwood, 2012) while international labor standards suggest the time acclimatized individuals spend doing low intensity labor such as office work be halved under such conditions (Kjellstrom et al., 2009a).[1] One estimate suggests global labor productivity will be reduced during the hottest months to 60% in 2100 and less than 40% in 2200 under the RCP8.5 scenario in which global mean temperatures rise 3.4°C by 2100 and 6.2°C by 2200 relative to 1861–1960 (Dunne et al., 2013). It is projected that tropical and mid-latitude regions including India, Northern Australia, and the southeastern USA will be particularly badly affected (Willett and Sherwood, 2012; Dunne et al., 2013).

11.8.2. Limits to Food Production and Human Nutrition

Agricultural crops and livestock similarly have physiological limitations in terms of thermal and water stress. For example, production of the staple crops maize, rice, wheat, and soybean is generally assumed to face an absolute temperature limit in the range of 40°C to 45°C (Teixeira et al., 2011), while key phenological stages such as sowing to emergence, grain-filling, and seed set have maximum temperature thresholds near or below 35°C (Yoshida et al., 1981; Porter and Gawith, 1999; Porter and Semenov, 2005). The existence of critical climatic thresholds and evidence of nonlinear responses of staple crop yields to temperature and rainfall (Brázdil et al., 2009; Schlenker and Roberts, 2009; Lobell et al., 2011b) thus suggest that there may be a threshold of global warming beyond which current agricultural practices can no longer support large human civilizations, and the impacts on malnourishment and undernutrition described in Section 11.6.1 will become much more severe. However, current models to estimate the human health consequences of climate-impaired food yields at higher global temperatures generally incorporate neither critical thresholds nor nonlinear response functions (Lloyd et al., 2011; Lake et al., 2012), reflecting uncertainties about exposure-response relations, future extreme events, the scale and feasibility of adaptation, and climatic thresholds for other influences such as infestations and plant diseases. Extrapolation from current models nevertheless suggests that the global risk to food security becomes very severe under an increase of 4°C to 6°C or higher in global mean temperature (*medium evidence*, *high agreement*) (Chapter 7, Executive Summary).

11.8.3. Thermal Tolerance of Disease Vectors

Substantial warming in higher-latitude regions will open up new terrain for some infectious diseases that are limited at present by low temperature boundaries, as already evidenced by the northward extensions in Canada and Scandinavia of tick populations, the vectors for Lyme disease and tick-borne encephalitis (Lindgren and Gustafson, 2001; Ogden et al., 2006). On the other hand, the emergence of new temperature regimes that exceed optimal conditions for vector and host species will reduce the potential for infectious disease transmission and, with high enough temperature rise, may eventually eliminate some infectious diseases that exist at present close to their upper tolerable temperature limits. For example, adults of two malaria-transmitting mosquito species are unable to survive temperatures much above 40°C in laboratory experiments (Lyons et al., 2012), although in the external world they may seek out tolerable microclimates. Reproduction of the malaria parasite within the mosquito is impaired at lesser raised temperatures (Paaijmans et al., 2009). Larval development of *Aedes albopictus*, an Asian mosquito vector of dengue and chikungunya, also does not occur at or above 40°C (Delatte et al., 2009).

11.8.4. Displacement and Migration Under Extreme Warming

Weather extremes and longer term environmental change including sea level rise lead to both more people displaced and increase in populations that are effectively trapped (Section 12.4.1.2). This trend is expected to be more pronounced under extreme levels of warming (Section 16.5). Gemenne (2011) argues that the most significant difference between the nature of human migration in response to 4°C of warming relative to 2°C would be to remove many people's ability to choose whether to stay or leave when confronted with environmental changes. Health studies of refugees, migrants, and people in resettlement schemes suggest that forced displacement, in turn, is likely to lead to more adverse health impacts than voluntary migration or planned resettlement (McMichael et al., 2012). The health risks associated with forced displacement include undernutrition; food- and water-borne illnesses; diseases related to overcrowding such as measles, meningitis, and acute respiratory infections; sexually transmitted diseases; increased maternal mortality; and mental health disorders (McMichael et al., 2012).

11.8.5. Reliance on Infrastructure

Under severe climate regimes, societies may be able to protect themselves by enclosing places for living and working, first for their most vulnerable

[1] WBGT is a heat index closely related to the wet-bulb temperature that also incorporates measures of radiant heat from the sun and evaporative cooling due to wind.

members: the young, old, ill, and manual laborers. This strategy will mean increased vulnerability to infrastructure failure and unreliable energy and water supplies. Electrical power outages have been linked to both accidental and disease-related deaths in temperate climates (Anderson and Bell, 2012), and failures in power supplies are more likely to occur during extreme weather events (Section 19.6.2.1). Large-scale reliance on air conditioning under a significantly hotter climate regime would therefore pose a serious health risk.

11.9. Co-Benefits

Essentially every human activity affects (and is affected by) climate and health status in some way, but not all are strongly linked to either and even fewer strongly to both. Here we focus on measures to mitigate the atmospheric concentration of warming climate-altering pollutants that also hold the potential to significantly benefit human health. These so-called co-benefits include health gains from strategies that are directed primarily at climate change, and mitigation of climate change from well-chosen policies for health advancement (Haines et al., 2007; Apsimon et al., 2009; Smith and Balakrishnan, 2009; UNEP, 2011; Shindell et al., 2012). The literature on health co-benefits associated with climate change mitigation strategies falls into several categories (Smith and Balakrishnan, 2009; Smith et al., 2009). These include:

- Reduce emissions of health-damaging pollutants, either primary or precursors to other pollutants in association with changes in energy production, energy efficiency, or control of landfills
- Increase access to reproductive health services
- Decrease meat consumption (especially from ruminants) and substitute low-carbon healthy alternatives
- Increase active transport particularly in urban areas
- Increase urban green space.

In addition, although not discussed here, there are potential health side effects of mitigation measures, such as geoengineering, biofuel expansion, and carbon taxes that are potentially deleterious for human health (Tilman et al., 2009; see Chapter 19). In Table 11-3, we summarize what is known about the main categories of co-benefits, but because of space limitation, we only provide additional detail for two of them below.

11.9.1. Reduction of Co-Pollutants

Most of the publications related to CAPs and health-damaging pollutants refer to fuel combustion and fall into three major categories: (1) improvement in energy efficiency will reduce emissions of CO_2 and health-damaging pollutants, providing these gains are not outpaced by increases in energy demand, and the energy is derived from combustion of fossil fuels or non-renewable biomass fuels, either directly or through the electric power system; (2) increases of combustion efficiency (decreasing emission of incomplete combustion products) will have both climate and health benefits, even if there is no change in energy efficiency and/or fuel itself is renewable, because a number of the products of incomplete combustion are climate altering and nearly all are damaging to health (Smith and Balakrishnan, 2009); and (3) increased use of non-combustion sources, such as wind, solar, tidal, wave, and geothermal energy, would reduce emissions of warming CAPs and health damaging air pollutants, providing benefits for climate and health (Jacobson et al., 2013).

Studies of the health co-benefits of reduction in air pollutants include sources that produce outdoor air pollution (Bell et al., 2008a) and household sources (Po et al., 2011). In many parts of the world, household fuels (poorly combusted biomass and coal) are responsible for a substantial percent of primary outdoor fine particle pollution as well, perhaps a quarter in India for example (Lim et al., 2012). In many parts of the world, household fuel (poorly combusted biomass and coal) is responsible for much fine particle outdoor air pollution and may contribute to long-range transport of hazardous air pollutants (Anenberg et al., 2013). This indicates that reductions in emissions from household sources will yield co-benefits through the outdoor pollution pathway.

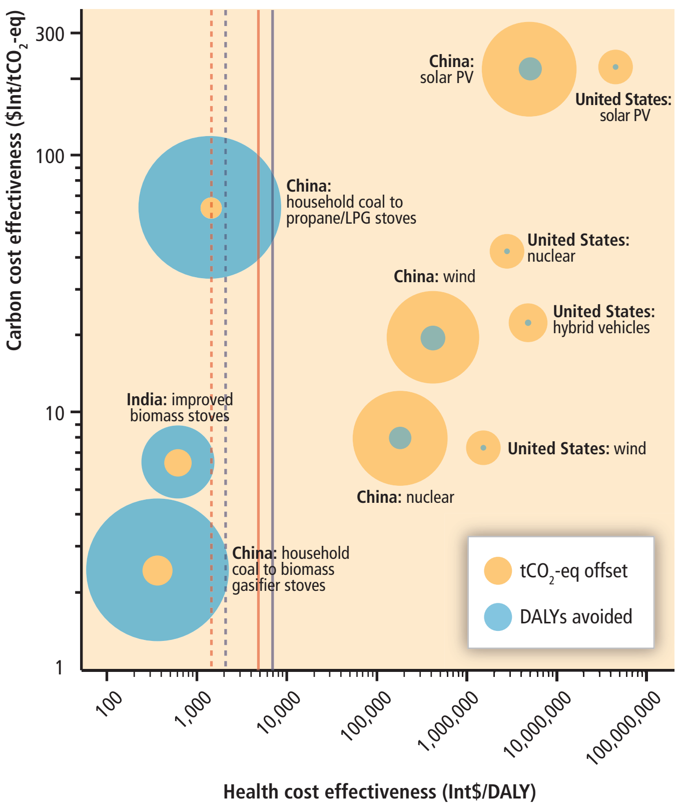

Figure 11-7 | Illustrative co-benefits comparison of the health and climate cost-effectiveness of selected household, transport, and power sector interventions (Smith and Haigler, 2008). Area of each circle denotes the total social benefit in international dollars (Int$) from the combined value of carbon offsets (valued at 10$/$tCO_2$-eq (tons of carbon dioxide equivalent)) and averted disability-adjusted life years (DALYs; $7450/DALY, which is representative of valuing each DALY at the average world gross domestic product (PPP) per capita in 2000). The vertical lines shows the range of the cut offs for cost-effective (solid lines) and very cost-effective (dashed lines) health interventions in India (red lines) and China (purple lines) using the WHO CHOICE (CHOosing Interventions that are Cost-Effective) criteria (WHO, 2003). This figure evaluates only a small subset of all co-benefits opportunities, and thus should not be considered either current or complete. It does illustrate, however, the kind of comparisons that can help distinguish and prioritize options. Note that even with the log-log scaling, there are big differences among them. For other figures comparing the climate and health benefits of co-benefits actions including those in food supply and urban design, see Haines et al. (2009). See the original reference for details of the calculations in this figure (Smith and Haigler, 2008).

Table 11-3 | Examples of recent (post-AR4) research studies on co-benefits of climate change mitigation and public health policies. For recent estimates of the global and regional burden of disease from the various risk factors involved, see Lim et al. (2012). (CAP = climate-altering pollutant.)

Co-benefit category	Benefits for health	Benefits for climate	References
Reduction of co-pollutants from household solid fuel combustion (see also WGIII AR5, Chapters 7 to 10)	Potentially reduce exposures that are associated with disease, chronic and acute respiratory illnesses, lung cancer, low birth weight and stillbirths, and possibly tuberculosis	Reduces CAP emissions associated with household solid fuel use including CO_2, CO, black carbon, and CH_4	Bell et al. (2008); Smith et al. (2008); Wilkinson et al. (2009); Lefohn et al. (2010); Venkataraman et al. (2010); World Health Organization Regional Office for Europe (2010); Po et al. (2011); Anenberg et al. (2012)
Reduction of greenhouse gases and associated co-pollutants from industrial sources, such as power plants and landfills, by more efficient generation or substitution of low carbon alternatives (Section 27.3.7.2)	Reductions in health-damaging co-pollutant emissions would decrease exposures to outdoor air pollution and could reduce risks of cardiovascular disease, chronic and acute respiratory illnesses, lung cancer, and preterm birth.	Reductions in emissions of CO_2, black carbon, CO, CH_4, and other CAPs	Bell et al. (2008); Apsimon et al. (2009); Jacobson (2009); Puppim de Oliveira et al. (2009); Smith et al. (2009); Tollefsen et al. (2009); Dennekamp et al. (2010); Jacobson (2010); Nemet et al. (2010); Rive and Aunan (2010); Shonkoff et al. (2011); Shindell et al. (2012); West et al. (2012); West et al. (2013)
Energy efficiency. Actual energy reduction may sometimes be less than anticipated because part of the efficiency benefit is taken as more service.	Reductions in fuel demand potentially can reduce emissions of CAPs associated with fuel combustion and subsequent exposures to pollutants that are known to be health damaging.	Reductions in emission of CAPs due to decreases in fuel consumption	Markandya et al. (2009); Wilkinson et al. (2009)
Increases in active travel and reductions in pollution due to modifications to the built environment, including better access to public transport and higher density of urban settlements (see also Sections 24.4, 24.5, 24.6, 24.7, 26.8)	Increased physical activity; reduced obesity; reduced non-communicable disease burden, health service costs averted; improved mental health; reduced exposure to air pollution; increased local access to essential services, including food stores; enhanced safety	Reductions of CAP emissions associated with vehicle transport; replacing existing vehicles with lower emission vehicles could reduce air pollution.	Babey et al. (2007); Reed and Ainsworth (2007); Kaczynski and Henderson (2008); Casagrande et al. (2009); Jarrett et al. (2009); Rundle et al. (2009); Woodcock et al. (2009); Durand et al. (2011); Grabow et al. (2011); McCormack and Shiell (2011); Jensen et al. (2013); Woodcock et al. (2013)
Healthy low greenhouse gas emission diets, which can have beneficial effects on a range of health outcomes (see also Table 11.3)	Reduced dietary saturated fat in some populations (particularly from ruminants) and replacement by plant sources associated with decreased risk of (ischemic) heart disease, stroke, colorectal cancer (processed meat consumption). Increased fruit and vegetable consumption can reduce risk of chronic diseases. Reduced CH_4 emissions due to a decreased demand for ruminant meat products would reduce tropospheric ozone.	Reductions in CO_2 and CH_4 emissions from energy-intensive livestock systems	McMichael et al. (2007); Friel et al. (2009); Sinha et al. (2009); Smith and Balakrishnan (2009); Jakszyn et al. (2011); Hooper et al. (2012); Pan et al. (2012); Xu et al. (2012)
Greater access to reproductive health services	Lower child and maternal mortality from increased birth intervals and shifts in maternal age	Potentially slower growth of energy consumption and related CAP emissions; less impact on land use change, etc.	Tsui et al. (2007); Gribble et al. (2009); Prata (2009); O'Neill et al. (2010); Diamond-Smith and Potts (2011); Potts and Henderson (2012); Kozuki et al. (2013)
Increases in urban green space (Table 25-5)	Reduced temperatures and heat island effects; reduced noise; enhanced safety; psychological benefits; better self-perceived health status	Reduces atmospheric CO_2 via carbon sequestration in plant tissue and soil	Mitchell and Popham (2007); Babey et al. (2008); Maas et al. (2009); van den Berg et al. (2010); van Dillen et al. (2011)
Carbon sequestration in forest plantations, reducing emissions from deforestation and degradation, and carbon offset sales (see Chapter 13 and Section 15.3.4; see also Sections 20.4.1 and 26.8.4.3)	Poverty alleviation and livelihood/job generation through sale of Clean Development Mechanism and voluntary market credits. Ameliorate declines in production or competitiveness in rural communities	Reduces emissions of CAPs and promotes carbon sequestration through reducing emissions from deforestation and degradation	Holmes (2010); Ezzine-de-Blas et al. (2011)

If interventions result in reductions in coal combustion, there are a range of other potential health benefits beyond reduction of particulate air pollution emissions, including reducing other types of health-damaging emissions and the human impacts from coal mining (Lockwood, 2012; Smith et al., 2013).

Another category of air pollution co-benefits comes from controls on methane emissions that both reduce radiative forcing and potentially reduce human exposures to ambient ozone, for which methane is a precursor.

11.9.1.1. Outdoor Sources

Primary co-pollutants, such as particulate matter (PM) and carbon monoxide (CO) are those released at the point of combustion, while secondary co-pollutants, such as tropospheric ozone and sulfate particles, are formed downwind from the combustion source via atmospheric chemical interactions (Jerrett et al., 2009) and can be transported long distances.

The burden of disease from outdoor exposures in a country may often be greater in populations with low socioeconomic status, both because of living in areas with higher exposures and because these populations often have worse health and are subjected to multiple additional negative environmental and social exposures (Morello-Frosch et al., 2011).

11.9.1.2. Household Sources

Globally, the largest exposures from the pollutants from poor fuel combustion occur in the poorest populations. This is because household use of biomass for cooking is distributed nearly inversely with income. Essentially, no poor family can afford gas or electricity for cooking and very few families who can afford to do so, do not. Thus, the approximate 41% of all world households using solid fuels for cooking are all among the poor in developing countries (Bonjour et al., 2013). Although biomass makes up the bulk of this fuel and creates substantial health impacts from products of incomplete combustion when burned in simple stoves (Lim et al., 2012), probably the greatest health and largest climate impacts per household result from use of coal, which can also be contaminated with sulfur and a range of toxic elements as well (Edwards et al., 2004; Zhang and Smith, 2007). Successfully accelerating the reduction of impacts from these fuels, however, has not been found to be easily accomplished with biomass/coal stove programs implemented to date and may require moving to clean fuels (Bruce et al., 2013). The climate benefits from improving household biomass fuel combustion come in part from potential reduction of net warming by reducing emissions of aerosols (including black carbon), but more confidently from reduction of CH_4 and other CAPs that are produced by incomplete combustion, as well as reductions in net CO_2 emissions if interventions are applied in areas relying on non-renewably harvested wood fuel (WGI AR5 Section 8.5.3).

11.9.1.3. Primary Co-Pollutants

Outdoor exposure to PM, especially to particles with diameters less than 2.5 μm ($PM_{2.5}$), contributes significantly to ill health including cardio- and cerebrovascular disease, adult chronic and child acute respiratory illnesses, lung cancer, and possibly other diseases. The Comparative Risk Assessment (CRA) for outdoor air pollution done as part of the Global Burden of Disease (GBD) 2010 Project found approximately 3.2 million premature deaths globally from ambient particle pollution or about 3% of the global burden of disease (Lim et al., 2012). Importantly, reductions in ambient PM concentrations have also been shown to decrease morbidity and premature mortality (Boldo et al., 2010). A significant portion of ambient particle pollution derives from fuel combustion, perhaps 80% globally (GEA, 2012).

Because of higher exposures, an additional set of diseases has also been associated with combustion products in households burning biomass and/or coal for cooking and heating. Thus, in addition to the diseases noted above, cataracts, low birth weight, and stillbirth have been associated strongly with exposures to incomplete combustion products, such as PM and CO. CO has impacts on unborn children *in utero* through exposures to their pregnant mothers (WHO Regional Office for Europe, 2010). There is also growing evidence of exacerbation of tuberculosis (Pokhrel et al., 2010) in adults and cognitive effects in children (Dix-Cooper et al., 2012). The CRA of the GBD-2010 found 3.5 million premature deaths annually from household air pollution derived from cooking fuels or 4.4% of the global burden of disease (Lim et al., 2012). Importantly, there are also studies showing health benefits of household interventions, for child pneumonia (Smith et al., 2011), blood pressure (McCracken et al., 2007; Baumgartner et al., 2011) , lung cancer (Lan et al., 2002), and chronic obstructive pulmonary disease (Chapman et al., 2005). Another half a million premature deaths are attributed to household cookfuel's contribution to outdoor air pollution, making a total of about 4 million in 2010 or 4.9% of the global burden of disease (Lim et al., 2012).

Black carbon (BC), a primary product of incomplete combustion, is both a strong CAP and health-damaging (IPCC, 2007; Ramanathan and Carmichael, 2008; Bond et al., 2013). A systematic review, meta-analysis, and the largest cohort study to date of the health effects of BC found that there were probably stronger effects on mortality from exposure to BC than for undifferentiated fine particles ($PM_{2.5}$) (Smith et al., 2009). Reviews have concluded that abatement of particle emissions including BC represents an opportunity to achieve both climate mitigation and health benefits (UNEP, 2011; Shindell et al., 2012). WGI AR5 (Box TS-6), however, concluded that the net impact of BC emissions reductions overall is not certain as to sign, i.e., whether net warming or cooling. Nevertheless, there would be co-benefits in circumstances where BC is emitted without many other cooling aerosols, as with diesel and kerosene combustion (Lam et al., 2012).

Other examples of climate forcing, health-damaging co-pollutants of CO_2 from fuel use are carbon monoxide, non-methane hydrocarbons, and sulfur and nitrogen oxides. Each co-pollutant poses risks as well as being climate altering in different ways. See WGI for more on climate potential and WHO reviews of health impacts (WHO, 2006; WHO Regional Office for Europe, 2010).

11.9.1.4. Secondary Co-Pollutants

In addition to being a strong GHG, methane is also a significant precursor to regional anthropogenic tropospheric ozone production, which itself is both a GHG and damaging to health, crops, and ecosystems (WGI AR5 TS.5.4.8). Thus, reductions in CH_4 could lead to reductions in ambient tropospheric ozone concentrations, which in turn could result in reductions in population morbidity and premature mortality and climate forcing.

One study found that a reduction of global anthropogenic CH_4 emissions by 20% beginning in 2010 could decrease the average daily maximum 8-hour surface ozone by 1 ppb by volume, globally—sufficient to prevent 30,000 premature all-cause mortalities globally in 2030, and 370,000 between 2010 and 2030 (West et al., 2012). CH_4 emissions are generally accepted as the primary anthropogenic source of tropospheric ozone concentrations above other human-caused emissions of ozone precursors (West et al., 2007b), and thus the indirect health co-benefits of CH_4 reductions are epidemiologically significant. On the other hand, work done for the GBD-2010 estimated 150,000 premature deaths from all ozone exposures globally in 2010, indicating a more conservative interpretation of the evidence for mortality from ozone (Lim et al., 2012).

In an analysis of ozone trends from 1998–2008 in the USA, Lefohn et al. (2010) found that 1-hour and 8-hour ambient ozone averages have either decreased or failed to increase due to successful regulations of ozone precursors, predominantly NO_x and CH_4. This is consistent with the EPA (2013) conclusion that in the USA, for the period 1980–2012, emissions of nitrogen oxides and volatile organic compounds fell by 59% and 57%, respectively (Lefohn et al., 2010; EPA, 2013). These results point to the effectiveness of reducing ambient ozone concentrations through regulatory tools that reduce the emissions of ozone precursors, some of which, like CH_4, are GHGs.

Not every CAP emitted from fuel combustion is warming. The most prominent example is sulfur dioxide emitted from fossil fuel combustion, which changes to particle sulfate in the atmosphere. Although health damaging, sulfate particles have a cooling effect on global radiative forcing. Thus, reduction of sulfur emissions, which is important for health protection, does not qualify as a co-benefit activity because it actually acts to unmask more of the warming effect of other CAP emissions (Smith et al., 2009).

11.9.1.5. Case Studies of Co-Benefits of Air Pollution Reductions

A recent United Nations Environment Programme (UNEP)- and World Meteorological Organization (WMO)-led study of BC and tropospheric ozone found that, if all of 400 proposed BC and CH_4 mitigation measures were implemented on a global scale, the estimated benefits to health would come predominately from reducing $PM_{2.5}$ (0.7 to 4.6 million avoided premature deaths; 5.3 to 37.4 million avoided years of life lost) compared to tropospheric ozone (0.04 to 0.52 million avoided premature deaths; 0.35 to 4.7 million avoided years of life lost) based on 2030 population figures (UNEP, 2011). About 98% of the avoided deaths would come from reducing $PM_{2.5}$, with 80% of the estimated health benefits occurring in Asia (Anenberg et al., 2012). Another study of the reduction of PM and ozone exposures due to CAPs emissions controls and including climate change feedback showed potential reductions of 1.3 million premature deaths by 2050 with avoided costs of premature mortality many times those of the estimated cost of abatement (West et al., 2013).

A study of the benefits of a hypothetical 10-year program to introduce advanced combustion cookstoves in India found that in addition to reducing premature mortality by about 2 million and DALYs by 55 million over that period, there would be a reduction of 0.5 to 1.0 billion tons CO2-eq (Wilkinson et al., 2009). Another study of India found a potential to reduce 570,000 premature deaths a year, one-third of national BC emissions, and 4% of all national GHG emissions by hypothetical substitution of clean household fuel technologies (Venkataraman et al., 2010).

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In their estimation of effects of hypothetical physical and behavioral modifications in UK housing, Wilkinson and colleagues (Wilkinson et al., 2009) found that the magnitude and direction of implications for health depended heavily on the details of the intervention. However, the interventions were found to be generally positive for health. In a strategy of housing modification that included insulation, ventilation control, and fuel switching, along with behavioral changes, it was estimated that 850 fewer DALYs, and a savings of 0.6 megatonnes of CO_2 per million population in 1 year, could be achieved. These calculations were made by comparing the health of the 2010 population with and without the specified physical and behavioral modifications (Wilkinson et al., 2009).

Markandya et al. (2009) assessed the changes in emissions of $PM_{2.5}$ and subsequent effects on population health that could result from climate change mitigation measures aimed to reduce GHG emissions by 50% by 2050 (compared with 1990 emissions) from the electricity generation sector in the EU, China, and India. In all three regions, changes in modes of production of electricity to reduce CO_2 emissions were found to reduce $PM_{2.5}$ and associated mortality. The greatest effect was found in India and the smallest in the EU. The analysis also found that if the health benefits were valued similarly to the approach used by the EU for air pollution, they offset the cost of GHG emission reductions, especially in the Indian context where emissions are high but costs of implementing the measures are low (Markandya et al., 2009).

11.9.2. Access to Reproductive Health Services

Population growth influences the consumption of resources and emissions of CAPs (Cohen, 2010). Although population growth rates and total population size do not alone determine emissions, population size is an important factor. One study showed that CO_2 emissions could be lower by 30% by 2100 if access to contraception was provided to those women expressing a need for it (O'Neill et al., 2012). Providing the unmet need for these services in areas such as the Sahel region of Africa that has both high fertility and high vulnerability to climate change can potentially significantly reduce human suffering as climate change proceeds (Potts and Henderson, 2012).

This is important not only in poor countries, however, but also some rich ones like the USA, where there is unmet need for reproductive health services as well as high CO_2 emissions per capita (Cohen, 2010). Also, because of income rise in developing countries and concurrent reduction of greenhouse emissions in developed countries, a convergence in emissions per capita is expected in most scenarios by 2100 (WGI AR5 TS.5.2). Slowing population growth through lowering fertility, as might be achieved by increasing access to family planning, has been associated with improved maternal and child health—the co-benefit—in two main ways: increased birth spacing and reducing births by very young and old mothers.

11.9.2.1. Birth and Pregnancy Intervals

Current evidence supports, with *medium confidence*, that short birth intervals (defined as birth intervals ≤24 months and inter-pregnancy intervals <6 months) are associated with increased risks of uterine rupture and bleeding (placental abruption and placenta previa) (Bujold et al., 2002; Conde-Agudelo et al., 2007).

There is also a correlation between short birth interval and elevated risk of low birth weight (Zhu, 2005). Zhu (2005) found, in a review of three studies performed in the USA, that the smallest risk of low birth weight was found with inter-pregnancy spacing between 18 and 23 months. Another review of five cohort studies found that a birth interval shorter than 18 months was significantly associated with increased low birth weight, preterm birth, and infant mortality after controlling for confounding factors (Kozuki et al., 2013).

Although an ecological analysis, a review across 17 countries shows a strikingly coherent picture of the relationship between birth spacing and reductions in child, infant, and neonatal mortality, with risk of child undernutrition and mortality both increasing with shorter birth intervals (Rutstein, 2005). One study estimated that shifting birth spacing from current patterns in the world to a minimum of 24 months would reduce by 20% (approximately 2 million) the current excess child mortality in the world (Rutstein, 2005; Gribble et al., 2009).

11.9.2.2. Maternal Age at Birth

Risk of death during delivery is highest in very young and very old mothers, and these are also the age groups that most often want to control their fertility (Engelman, 2010). Women who begin child bearing under the age of 20 years are at an increased risk of developing pregnancy complications such as cephalopelvic disproportion, obstructed labor, preterm delivery, toxemia, bleeding, and maternal death (Tsui et al., 2007). In addition, children born to women younger than the age of 20 are at increased risk of fetal growth retardation and low birth weight, both of which can lead to long-term physical and mental developmental problems (Tsui et al., 2007). Childbearing at later ages (>35 years) is associated with increased risk of miscarriage and other adverse health outcomes (Cleary-Goldman et al., 2005; Ujah et al., 2005).

Providing access to family planning saves women's lives by reducing the total number of births and, in particular, through the reduction of births in high-risk groups (Prata, 2009) while simultaneously reducing total fertility and subsequent CAP emissions. Studies have found that when women have access to family planning, it is the highest risk age groups (youngest and oldest women) who reduce their fertility the most. In other words, family planning has a differential impact on maternal mortality reduction through reducing births in the highest risk groups (Diamond-Smith and Potts, 2011).

11.10. Key Uncertainties and Knowledge Gaps

There is evidence that poverty alleviation, public health interventions such as provision of water and sanitation, and early warning and response systems for disasters and epidemics will help to protect health from climate risks. The key uncertainty is the extent to which society will strengthen these services, including taking into account the risks posed by climate change. With a strong response, climate change health effects are expected to be relatively small in the next few decades, but otherwise climate-attributable cases of disease and injury will steadily increase.

Since AR4, national governments, through the World Health Assembly, have specifically called for increased research on (1) the scale and nature of health risks from climate change; (2) effectiveness of interventions to protect health; (3) health implications of adaptation and mitigation decisions taken in other sectors, (4) improvement in decision support systems and surveillance, and (5) estimation of resource requirements. A recent scoping review identified quantitative peer-reviewed studies across all of these areas, with the exception of studies on the effectiveness or cost-effectiveness of targeted adaptation measures (Hosking and Campbell-Lendrum, 2012). There are also comparatively few studies of vulnerability in low- and middle-income populations, or of more complex disease pathways, such as the effect of more extreme weather on water and sanitation provision and diarrhea rates, on zoonotic diseases, or mental health. Studies of health co-benefits of climate change mitigation policies also remain rare compared to the size of the potential health gains. Potential negative side effects also need to be addressed, for example those arising from biofuel policies that compete with food production.

Relevant research for health protection in the near term is therefore likely to come from cross-disciplinary studies, including public health decision makers, in the following areas: improved vulnerability and adaptation assessments that focus on particularly vulnerable populations and encompass complex causal pathways; quantitative estimation of the effectiveness of health adaptation measures; surveillance, monitoring, and observational systems that link climate, health, and economic impact data and provide a basis for early warning systems as well as development of future scenarios; and assessment of the health co-benefits of alternative climate mitigation policies.

In the longer term, research will need to make the best use of traditional epidemiologic methods, while also taking into account the specific characteristics of climate change. These include the long-term and uncertain nature of the exposure and effects on multiple physical and biotic systems, with the potential for diverse and widespread effects, including high-impact events. There are low-probability, but plausible, scenarios for extreme climate regimes before the end of the century. Although difficult, it is important to develop robust methods to investigate the health implications of conditions that may apply in 2100, as decisions today about mitigation will determine their likelihood. Given the increase globally in life expectancies, many babies born this decade will be alive at the end of the century, and will be personally affected by the climate that is in place in 2100.

Frequently Asked Questions

FAQ 11.1 | How does climate change affect human health?

Climate change affects health in three ways: (1) directly, such as the mortality and morbidity (including "heat exhaustion") due to extreme heat events, floods, and other extreme weather events in which climate change may play a role; (2) indirect impacts from environmental and ecosystem changes, such as shifts in patterns of disease-carrying mosquitoes and ticks, or increases in waterborne diseases due to warmer conditions and increased precipitation and runoff; and (3) indirect impacts mediated through societal systems, such as undernutrition and mental illness from altered agricultural production and food insecurity, stress, and violent conflict caused by population displacement; economic losses due to widespread "heat exhaustion" impacts on the workforce; or other environmental stressors, and damage to health care systems by extreme weather events.

Frequently Asked Questions

FAQ 11.2 | Will climate change have benefits for health?

Yes. For example some populations in temperate areas may be at less risk from extreme cold, and may benefit from greater agricultural productivity, at least for moderate degrees of climate change. Some areas currently prone to flooding may become less so. However, the overall impact for nearly all populations and for the world as a whole is expected to be more negative than positive, increasingly so as climate change progresses. In addition, the latitude range in the world that may benefit from less cold (e.g., the far north of the Northern Hemisphere) has fewer inhabitants compared with the equatorial latitudes where the burden will be greatest.

Frequently Asked Questions

FAQ 11.3 | Who is most affected by climate change?

While the direct health effects of extreme weather events receive great attention, climate change mainly harms human health by exacerbating existing disease burdens and negative impacts on daily life among those with the weakest health protection systems, and with the least capacity to adapt. Thus, most assessments indicate that poor and disenfranchised groups will bear the most risk and, globally, the greatest burden will fall on poor countries, particularly on poor children, who are most affected today by such climate-related diseases as malaria, undernutrition, and diarrhea. However, the diverse and global effects of climate change mean that higher income populations may also be affected by extreme events, emerging risks, and the spread of impacts from more vulnerable populations.

Frequently Asked Questions

FAQ 11.4 | What is the most important adaptation strategy to reduce the health impacts of climate change?

In the immediate future, accelerating public health and medical interventions to reduce the present burden of disease, particularly diseases in poor countries related to climatic conditions, is the single most important step that can be taken to reduce the health impacts of climate change. Priority interventions include improved management of the environmental determinants of health (such as provision of water and sanitation), infectious disease surveillance, and strengthening the resilience of health systems to extreme weather events. Alleviation of poverty is also a necessary condition for successful adaptation.

There are limits to health adaptation, however. For example, the higher-end projections of warming indicate that before the end of the 21st century, parts of the world may experience temperatures that exceed physiological limits during periods of the year, making it impossible to work or carry out other physical activity outside.

Frequently Asked Questions

FAQ 11.5 | What are health "co-benefits" of climate change mitigation measures?

Many mitigation measures that reduce emissions of those climate-altering pollutants (CAPs) that warm the planet have important direct health benefits in addition to reducing the risk of climate change. This relationship is called "co-benefits." For example, increasing combustion efficiency in households cooking with biomass or coal could have climate benefits by reducing CAPs and at the same time bring major health benefits among poor populations. Energy efficiency and reducing reliance on coal for electricity generation not only reduces emissions of greenhouse gases, but also reduces emissions of fine particles that cause many premature deaths worldwide as well as reducing other health impacts from the coal fuel cycle. Programs that encourage "active transport" (walking and cycling) in place of travel by motor vehicle reduce both CAP emissions and offer direct health benefits. A major share of greenhouse gas emissions from the food and agriculture sector arises from cows, goats, and sheep—ruminants that create the greenhouse gas methane as part of their digestive process. Reducing consumption of meat and dairy products from these animals may reduce ischemic heart disease (assuming replacement with plant-based polyunsaturates) and some types of cancer. Programs to provide access to reproductive health services for all women will not only lead to slower population growth and its associated energy demands, but also will reduce the numbers of child and maternal deaths.

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12 Human Security

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Executive Summary

Human security will be progressively threatened as the climate changes (*robust evidence*, *high agreement*). Human insecurity almost never has single causes, but instead emerges from the interaction of multiple factors. {12.1.2, 12.2} Climate change is an important factor threatening human security through (1) undermining livelihoods {12.2}; (2) compromising culture and identity {12.3}; (3) increasing migration that people would rather have avoided {12.4}; and (4) challenging the ability of states to provide the conditions necessary for human security. {12.6}

Climate change will compromise the cultural values that are important for community and individual well-being (*medium evidence*, *high agreement*). The effect of climate change on culture will vary across societies and over time, depending on cultural resilience and the mechanisms for maintaining and transferring knowledge. Changing weather and climatic conditions threaten cultural practices embedded in livelihoods and expressed in narratives, world views, identity, community cohesion, and sense of place. Loss of land and displacement, for example on small islands and coastal communities, has well documented negative cultural and well-being impacts. {12.3.1, 12.3.3, 12.4.2}

Indigenous, local, and traditional forms of knowledge are a major resource for adapting to climate change (*robust evidence*, *high agreement*). Natural resource dependent communities, including indigenous peoples, have a long history of adapting to highly variable and changing social and ecological conditions. But the salience of indigenous, local, and traditional knowledge will be challenged by climate change impacts. Such forms of knowledge are often neglected in policy and research, and their mutual recognition and integration with scientific knowledge will increase the effectiveness of adaptation. {12.3.3-4}

Climate change will have significant impacts on forms of migration that compromise human security (*medium evidence*, *high agreement*). Some migration flows are sensitive to changes in resource availability and ecosystem services. Major extreme weather events have in the past led to significant population displacement, and changes in the incidence of extreme events will amplify the challenges and risks of such displacement. Many vulnerable groups do not have the resources to be able to migrate to avoid the impacts of floods, storms, and droughts. Models, scenarios, and observations suggest that coastal inundation and loss of permafrost can lead to migration and resettlement. {12.4.2} Migrants themselves may be vulnerable to climate change impacts in destination areas, particularly in urban centers in developing countries. {12.4.1.2}

Mobility is a widely used strategy to maintain livelihoods in response to social and environmental changes (*medium evidence*, *high agreement*). Migration and mobility are adaptation strategies in all regions of the world that experience climate variability. Specific populations that lack the ability to move also face higher exposure to weather-related extremes, particularly in rural and urban areas in low- and middle-income countries. Expanding opportunities for mobility can reduce vulnerability to climate change and enhance human security. {12.4.1-2} There is insufficient evidence to judge the effectiveness of resettlement as an adaptation to climate change.

Some of the factors that increase the risk of violent conflict within states are sensitive to climate change (*medium evidence*, *medium agreement*). The evidence on the effect of climate change and variability on violence is contested. {12.5.1} Although there is little agreement about direct causality, low per capita incomes, economic contraction, and inconsistent state institutions are associated with the incidence of violence. {12.5.1} These factors can be sensitive to climate change and variability. Poorly designed adaptation and mitigation strategies can increase the risk of violent conflict. {12.5.2}

People living in places affected by violent conflict are particularly vulnerable to climate change (*medium evidence*, *high agreement*). Evidence shows that large-scale violent conflict harms infrastructure, institutions, natural capital, social capital, and livelihood opportunities. Since these assets facilitate adaptation to climate change, there are grounds to infer that conflict strongly influences vulnerability to climate change impacts. {12.5.3}

Climate change will lead to new challenges to states and will increasingly shape both conditions of security and national security policies (*medium evidence*, *medium agreement*). Physical aspects of climate change, such as sea level rise, extreme events, and hydrologic disruptions, pose major challenges to vital transport, water, and energy infrastructure. {12.6} Some states are experiencing major challenges to their territorial integrity, including small island states and other states highly vulnerable to sea level rise. {12.6.2} Some transboundary impacts of climate change, such as changes in sea ice, shared water resources, and the migration of fish stocks, have the potential to increase rivalry among states. The presence of robust institutions can manage many of these rivalries such that human security is not severely eroded. {12.5.1, 12.6.2}

12.1. Definition and Scope of Human Security

There are many definitions of human security, which vary according to discipline. This chapter defines human security, in the context of climate change, as a condition that exists when the vital core of human lives is protected, and when people have the freedom and capacity to live with dignity. In this assessment, the vital core of human lives includes the universal and culturally specific, material and non-material elements necessary for people to act on behalf of their interests. Many phenomena influence human security, notably the operation of markets, the state, and civil society. Poverty, discrimination of many kinds, and extreme natural and technological disasters undermine human security.

The concept of human security has been informed and debated by many disciplines and multiple lines of evidence, by studies that use diverse methods (Paris, 2001; Alkire, 2003; Owen, 2004; Gasper, 2005; Hoogensen and Stuvøy, 2006; Mahoney and Pinedo, 2007; Brauch et al., 2009; Inglehart and Norris, 2012). The concept was developed in parallel by UN institutions, and by scholars and advocates in every region of the world (UNDP, 1994; Commission on Human Security, 2003; Najam, 2003; Kaldor, 2007; Black and Swatuk, 2009; Chourou, 2009; Othman, 2009; Poku and Sandkjaer, 2009; Rojas, 2009; Sabur, 2009; Wun Gaeo, 2009).

This chapter assesses the risks climate change poses to individuals and communities, including threats to livelihoods, culture, and political stability. Chapters in Working Group II (WGII) in the Fourth Assessment Report (AR4) identified the risk climate change poses to livelihoods, cultures, and indigenous peoples globally (Chapters 5, 7, 9 10, 16, and 17) and that migration and violent conflicts increase vulnerability to climate change (Chapter 19), as well as highlighting that migration plays a role in adaptation. But this chapter is the first systematic assessment across the dimensions of human security.

Research since publication of the AR4 has addressed the linkages between climate change and human security through concerted international research programs and initiatives (Afifi and Jäger, 2010; Matthew et al., 2010; O'Brien et al., 2010; Gleditsch, 2012; Oswald Spring, 2012; Scheffran et al., 2012a; Sygna et al., 2013). Specific dimensions of human security, such as food security, public health and well-being, livelihoods, and regional perspectives, are examined systematically in Chapters 11, 13, and 19, and in Chapters 22 to 29 of this report, and this chapter cross-refers to those assessments.

The assessment in this chapter is based on structured reviews of scientific literature. These were carried out first using searches of scientific databases of relevant studies published from 2000 until 2013, with searches targeted at the core dimensions of culture, indigenous peoples, traditional knowledge, migration, conflict, and transboundary resources. These searches were supplemented by open searches to capture book and other non-journal literature. The comprehensive review in this chapter reflects the dominant findings from the scientific literature that the impacts of climate change on livelihoods, cultures, migration, and conflict are negative, but that some dimensions of human security are less sensitive to climate change and driven by economic and social forces.

This chapter assesses research on how climate change may exacerbate specific threats to human security, and how factors such as lack of mobility or the presence of conflict restrict the ability to adapt to climate change. Research on the specific interaction of human security and climate change focuses on how cultural, demographic, economic, and political forces interact with direct and indirect climate change impacts, affecting individuals and communities (Krause and Jütersonke, 2005; Hoogensen and Stuvøy, 2006; O'Brien, 2006; Betancourt et al., 2010; Sygna et al., 2013). The analysis concerns drivers of vulnerability across multiple scales and sectors, including gender relations, culture, political institutions, and markets. Each of these areas has its distinct disciplinary focus, methods, and levels of evidence as discussed in Box 12-2.

Human security and insecurity are universal issues. In every country there are individuals and groups who are insecure (Mahoney and Pinedo, 2007; Pietsch and McAllister, 2010). Much research suggests that while the impacts of climate change on human security will be experienced

Box 12-1 | Relationship between Human Rights and Human Security in the Context of Climate Change

This chapter focuses on human security, but does not explicitly frame the issue as one of rights. The argument is made in political and legal scholarship that human rights to life, health, shelter, and food are fundamentally breached by the impacts of climate change. Climate change puts both human security and human rights at risk (Slade, 2007; Caney, 2010; Humphreys, 2010). But framing the issue of rights specifies minimum standards that apply universally, and such rights are often not realized in national and international law and practice or neglect the harm or rights of nonhuman species (Humphreys, 2010; Bell, 2013). Human security by contrast is inclusive of political, sociocultural, and economic rights, rather than legal rights (CHS, 2003), which are instrumental to its achievement (Bell, 2013).

Research on climate change risks to human rights examines legal issues in policy, litigation, and compensation (Posner, 2007). Many legal commentators argue that claims to human rights may ultimately not offer greater explanation of the harm to individuals or realize political traction in climate policy (Carlane and Depledge, 2007; Adelman, 2010; Bodansky, 2010). Several cases have tested these rights, especially of women, children, indigenous peoples, and other minorities (Oswald Spring, 2008; Knox, 2009; Bodansky, 2010).

Box 12-2 | The Nature of Evidence about Climate Change and Human Security

Understanding the effects of climate change on human security requires evidence about social and environmental processes across multiple scales and sectors. This process-based analysis is informed by a wide array of theories, methods, and evidence used in different academic disciplines, and so is not contiguous. For example, this chapter assesses anthropological research where culture influences responses to climate change or may be shaped by climate change; alongside political and economic studies which use data sets to test for correlations between climatic factors and violent conflicts; and historical observations using documentary and archaeological methods. These diverse sources strengthen the robustness of the conclusions for this assessment when they converge on similar findings (Van de Noort, 2011; Nielsen and Reenberg, 2012).

This chapter reviews empirical studies from the social and physical sciences using both quantitative and qualitative data. Some studies examine the interactions between environmental changes and social outcomes. Few explicitly address climate change and human security links, but provide evidence of climate change impacts on human security (Ford et al., 2010). Individual case studies often make causal claims in given contexts, but their results may not be generalized. Where results from multiple comparative case studies agree, generalization is sometimes possible. This chapter also assesses quantitative studies about large social units with correlations among different factors. Correlations alone do not explain causality, although they are important in testing theories.

Given the many and complex links between climate change and human security, uncertainties in the research on the biophysical dimensions of climate change, and the nature of the social science, highly confident statements about the influence of climate change on human security are not possible (Scheffran et al., 2012a). Yet there is good evidence about many of the discrete links in the chains of causality between climate change and human insecurity. In this chapter the standardized IPCC language of uncertainty is applied to those linkages where appropriate.

Many climate change risks to human security warrant further investigation. There is a need for more comprehensive evidence, collected across multiple locations, and over long durations, to build and test theories about relationships between climate change and livelihoods, culture, migration, and conflict. Meeting this need requires analysis of the sensitivity of diverse livelihood systems to climate change; and the effects of cultural, economic, and political changes on the vulnerability and adaptability of livelihoods. Questions surrounding the cultural dimensions of climate require much more research using multiple methods to enable more general conclusions to be drawn, in particular about the effects of culture on climate change mitigation and adaptation. The sensitivity of human mobility to climate also requires new investigation, including, importantly, systematic long-term monitoring of population changes. The effects of migration on the vulnerability and adaptation of migrants, migrant sending areas, and destination communities also warrants more research, to permit scope for targeted policy interventions to reduce vulnerability. Finally, with respect to advancing knowledge of climate change and violence, extensive as well as case-based research is necessary to build theories of causality, including examination of cases where climate changes and variability were managed peacefully, in addition to cases where conflict emerged. Explanations of processes that reduce violence despite climate variability and change are necessary for responses that help sustain and improve peace in a future where the climate is changing.

most in developing countries, human security is at risk for vulnerable populations everywhere (Naess et al., 2006; Leichenko and O'Brien, 2008; Berrang-Ford et al., 2011).

The chapter also evaluates research on the interaction between the state and human security, suggesting that increased human insecurity may coincide with a decline in the capacity of states to conduct effective adaptation efforts, thus creating circumstances in which there is greater potential for violent conflict, especially in the absence of means to resolve conflicts effectively. The analysis extends to assess how states protect the human security of their citizens. In other words, this chapter examines the security of the state because it directly impinges on human security by affecting the ability of states to protect their citizens.

The framing of climate change as a security issue has been controversial. Some authors suggest that discourses on climate change and national security tend to downplay human security dimensions and skew mitigation and adaptation responses toward state interests rather than those of the most vulnerable human populations (Barnett 2007, 2009; Floyd, 2008; Brauch, 2009; Dalby, 2009; Verhoeven, 2009; Trombetta, 2012; Oels, 2013). Nevertheless, some countries associate climate change risks with conventional security risks and many countries are concerned about the risks climate change poses to relations between states (see Sections 12.5 and 12.6). This chapter therefore adopts a comprehensive approach to human security, which is widely supported in the literature (Barnett, 2001; Brauch et al., 2008, 2009, 2011; Matthew et al., 2010; O'Brien et al., 2010; Oswald Spring, 2012).

12.2. Economic and Livelihood Dimensions of Human Security at Risk from Climate Change

12.2.1. Climate Change Impacts on Material Aspects of Livelihood Security

The direct and material aspects of livelihood security include access to food, housing, clean water, employment, and the avoidance of direct risks to health. Chapters 7, 11, and 13 assess the evidence of the mechanisms that link climate change with these phenomena. They find that climate change poses significant risks in all these areas and all conclude that material aspects of life and livelihood such as food, water, and shelter are closely coupled to weather and climate but also to multiple factors in the economy and society (Battisti and Naylor, 2009; Bohle, 2009; Hertel et al., 2010; Schlenker and Lobell, 2010; Deligiannis, 2012; see also Section 13.1.4). Hence, although attributing changes in climate directly to human security is difficult, some major risks are well documented. This chapter builds on that knowledge base to assess the interaction of those risks with cultural dimensions of change, and the risks of migration and conflict. It is well established that direct risks of climate change to life and livelihoods are highly differentiated by socio-demographic factors, such as by age, wealth, and gender. Box CC-GC, for example, highlights how specific populations of men and women are vulnerable to weather extremes.

Table 12-1 summarizes studies that exemplify how climate variability and change affect the material aspect of human security through deprivation of immediate basic needs and erosion of livelihood assets

Table 12-1 | Illustrative examples of impacts of climate variability and change on immediate basic needs and longer term capabilities and assets from observational studies and from projections.

Dimensions of impact		Illustrative examples of observed impacts due to aggravating climate stresses	Illustrative examples of potential changes in livelihoods and capabilities as a consequence of climate variability and climate change
Deprivation of basic needs	Livelihood assets	Household assets such as livestock sold or lost during drought: documented examples are the 1999–2000 drought, Ethiopia, and 1999–2004 drought, Afghanistan (Carter et al., 2007; de Weijer 2007). Riverbank erosion, floods, and groundwater depletion and salinization are associated with changed hydrological regimes and cause loss of agricultural land (Paul and Routray, 2010; Taylor et al., 2013).	Simulated future climate volatility leads to reduced future production of staple grains and increases in poverty (Ahmed et al., 2009). Changes in the viability of livestock feed crops have an impact on smallholder farmers: maize yields are projected to decline in many regions (Jones and Thornton, 2003; Section 7.4). Projections of land loss, riverbank erosion, and groundwater depletion, in combination with environmental change and human interventions, suggest future stress on livelihood assets (Le et al., 2007; Taylor et al., 2013).
	Water stress and scarcity	Glacier retreat leads to lower river flows and hence affects water stress and livelihoods, representing a cultural loss (Orlove et al., 2008). For example, glacier recession in the Cordillera Blanca in Peru has altered the hydrological regime with implications for local livelihoods and water availability downstream (Mark et al., 2010).	Projected stresses to water availability show increased populations without sustainable access to safe drinking water (Hadipuro, 2007). Projected reduction in glacier extent and the associated loss of a hydrological buffer is expected to increase (Vuille, 2008; Section 3.4.4).
	Loss of property and residence	Floods destroy shelter and properties and curtail ability to meet basic needs. For example, the Fiji flood in 2009 resulted in economic losses of F$24 million affecting at least 15% of farm households (Lal, 2010). Sea level rise and increased frequency of extreme events increases the risk of loss of lives, homes, and properties and damages infrastructure and transport systems (Adrianto and Matsuda, 2002; Suarez et al., 2005; Philips and Jones, 2006; Ashton et al., 2008; Von Storch et al., 2008).	Changes in flood risk may increase and cause economic damages: in the Netherlands, the total amount of urban area that can potentially be flooded has increased sixfold during the 20th century and may double again during the 21st century (de Moel et al., 2011). In England and Wales, projected changes in flood risk mean economic damages may increase up to 20 times by the 2080s (Hall et al., 2003).
Erosion of livelihood and human capabilities	Agriculture and food security	Interaction of climate change with poverty and other political, social, institutional, and environmental factors may adversely affect agriculture production and exacerbate the problem of food insecurity (Downing, 2002; Saldana-Zorrilla, 2008; Trotman et al., 2009). Examples include in Kenya (Oluoko-Odingo, 2011); in Southern Africa (Drimie and Gillespie, 2010); in Zimbabwe and Zambia (Mubaya et al., 2012).	Studies of African agriculture using diverse climate scenarios indicate increasing temperature and rainfall variation have negative impacts on crops and livestock production and lead to increased poverty, vulnerability, and loss of livelihoods. Examples include Ethiopia (Deressa and Hassan, 2009); Kenya (Kabubo-Mariara, 2009); Burkina Faso, Egypt, Kenya, and South Africa (Molua et al., 2010); and sub-Saharan Africa (Jones and Thornton, 2009). Potential livelihood insecurity among small-scale rain-fed maize farmers in Mexico is projected owing to potential loss of traditional seed sources in periods of climate stress (Bellona et al., 2011).
	Human capital (health, education, loss of lives)	Food shortage, absence of safe and reliable access to clean water and good sanitary conditions, and destruction of shelters and displacements all have a negative bearing on human health (Costello et al., 2009; Sections 11.4 and 11.8). Droughts and floods can intensify the pressure to transfer children to the labor market (Ethiopia and Malawi; UNDP, 2007). Indian women born during a drought or flood in the 1970s were 19% less likely to ever attend primary school, when compared with women of the same age who were not affected by natural disasters (UNDP, 2007).	Analysis of the economic and climatic impacts of three emission scenarios and three tax scenarios estimates the impacts on food productivity and malaria infection to be very severe in some Asian countries (Kainuma et al., 2004). Studies of the impacts of future floods using a combination of socioeconomic and climate change scenarios for developed countries show an increase in mortality. For example, in the Netherlands, sea level rise, combined with other factors, potentially increases the number of fatalities four times by 2040 (Maaskant et al., 2009).

Frequently Asked Questions

FAQ 12.1 | What are the principal threats to human security from climate change?

Climate change threatens human security because it undermines livelihoods, compromises culture and individual identity, increases migration that people would rather have avoided, and because it can undermine the ability of states to provide the conditions necessary for human security. Changes in climate may influence some or all of the factors at the same time. Situations of acute insecurity, such as famine, conflict, and sociopolitical instability, almost always emerge from the interaction of multiple factors. For many populations that are already socially marginalized, resource dependent, and have limited capital assets, human security will be progressively undermined as the climate changes.

and human capabilities. There are well-established links from climate variability and change to the stability of agriculture and food security, water stress and scarcity, as well as destruction of property (Carter et al., 2007; Leary et al., 2008; Paavola, 2008; Peras et al., 2008; Tang et al., 2009). Projections using various socioeconomic and climate change scenarios indicate an increase in economic and health risks, including loss of lives in all regions (Hall et al., 2003; Kainuma et al., 2004; Tang et al., 2009) as well as a range of psychological stresses accompanying extreme climate events and decreased access to ecosystem resources (e.g., Doherty and Clayton, 2011). The cross chapter box on Heat Stress (Box CC-HS), for example, documents the evidence on the impacts of heat stress on both labor productivity and on health outcomes.

Modeled and observational analysis of human exposure to climate-related natural disasters finds significant risk of large human losses, particularly in countries with significant populations in poverty (Peduzzi et al., 2009; Busby et al., 2013). Table 12-1, and the analysis in cognate chapters (Sections 7.3, 11.3, 13.2.2), shows that risks are significant and well understood though there is uncertainty about how dimensions of basic needs, livelihoods, and the integrity of place and economic assets will unfold under scenarios of climate change. Those cognate chapters confirm that elements of nutrition, economic stability, and threats to shelter and human health interact with each other and all represent significant challenges for adaptation. Following from this body of evidence, a number of studies conclude that adverse impacts of climate change on health and on human capital will lead to the erosion of human capability (UNDP, 2007; Costello et al., 2009).

12.2.2. Adaptation Actions and Livelihood Dimensions of Human Security

Adaptation strategies seek to reduce vulnerability and thereby advance human security. But they also run the risk of exacerbating elements of insecurity (e.g., Deligiannis, 2012; see also Section 12.2.2). Evaluations of development interventions, for example, provide robust evidence on how livelihoods can be secured and enhanced through adaptation in the context of external shocks and shorter-term climate stresses (e.g., Ellis, 2000; Dercon, 2004). But an emerging literature documents how some adaptation interventions can create new risks, are inefficient, or fail to recognize wider goals of system resilience (e.g., Eriksen et al., 2011; Adger et al., 2011b; see also Sections 13.3.2 and 20.3.2).

Adaptation interventions and strategies have been documented that reduce risks to human security, but vary in effectiveness. Strategies that have been documented as promoting well-being include (1) diversification of income-generating activities in agricultural and fishing systems (Coulthard, 2008; Paavola, 2008; Tolossa, 2008; Galvin, 2009; Badjeck et al., 2010; West and Hovelsrud, 2010); (2) migration as a risk management strategy, for example, among pastoralists and farmers in rainfed areas (Galvin, 2009) and among fishing communities (Perry and Sumaila, 2007; Badjeck et al., 2009); (3) the development of insurance systems, particularly among vulnerable groups (Linneroth-Bayer and Vari, 2008; Badjeck et al., 2010); and (4) the education of women (Boyle et al., 2006; Rammohan and Johar, 2009). Some adaptation strategies may, however, undermine human security, particularly where strategies are implemented without taking cognizance of complex livelihood arrangements. In some cases, adaptations may entrench vulnerabilities and also have the potential to enforce inequalities (Barnett and O'Neill, 2010). For example, in parts of the Middle East and North Africa, the Andes, and the Caribbean, among other areas, skewed water policy allocation in some cases that favor the affluent may heighten overall livelihood vulnerabilities to climate stress (Section 13.2.1.1).

12.3. Cultural Dimensions of Human Security

12.3.1. How Culture Interacts with Climate Impacts and Adaptation

Culture is a contested and highly fluid term that is defined in this chapter as material and non-material symbols that express collective meaning. In all societies culture is expressed in knowledge, worldviews, beliefs, norms, values, and social relationships (Crate, 2008, 2011; Heyd, 2008; Roncoli et al., 2009; Strauss, 2009; O'Brien and Wolf, 2010; Tingley et al., 2010; Rudiak-Gould, 2012; Sudmeier-Rieux et al., 2012). In this definition culture shapes the relationship of society to environments and is a significant determinant of responses to environmental and other risks and challenges (Siurua and Swift, 2002; Pearce et al., 2009; Buikstra et al., 2010; Nielsen and Reenberg, 2010; Petheram et al., 2010; Paul and Routray, 2011).

There has been significant new research from psychology, anthropology, sociology, and human geography in the period since AR4 on the lived experience of weather extremes and observed climate change, driven

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Box 12-3 | Food Prices, Food Insecurity, and Links to Climate

Food prices and food-price shocks have significant impacts on human security. They do so through reduced access to, and production of, food that affects both consumers and food producers (e.g., Sections 7.4.3, 13.2.1-2; Barrett, 2010). It is well established that food security is determined by a range of interacting factors including poverty, water availability, food policy agreements and regulations, and the demand for productive land for alternative uses (Barrett, 2010, 2013). It is also established that many of these factors are themselves sensitive to climate variability and climate change. Specific observed food prices have, however, multiple causes and complex dynamics between markets, non-food demand for agricultural land, and the impact of adverse weather and droughts on the major agricultural producing regions (Piesse and Thirtle, 2009).

Spikes in food prices have particularly acute impacts on food insecurity at the domestic level, even in the absence of climate stresses. There was, for example, high regional variation in self-reported food insecurity following the global 2008 price spike: the reported food insecurity was especially serious across Africa and Latin American countries (Headey, 2013). The 2010–2011 food price spike has been estimated to have pushed 44 million people below the basic needs poverty line across 28 countries (Ivanic et al., 2012). Food availability can also be affected by domestic production of food, particularly for those countries where there are restrictions on food imports (Barrett, 2013; Berazneva and Lee, 2013). There are, therefore, multiple pathways by which consumers including agricultural wage laborers in low-income countries are affected (Mendelsohn et al., 2007; Ahmed et al., 2009; Cohen and Garrett, 2010; Hertel and Rosch, 2010; Ruel at al., 2010). Declines in agricultural productivity linked to climate variability and losses in maize production, for example, have been shown in Zambia to reduce real urban incomes and to influence urban poverty for a portion of the population (Thurlow et al., 2012).

Food prices and food availability also affect socio-political stability and in the case of the 2008–2009 and 2010–2011 food price spikes have been associated with food riots (Johnstone and Mazo, 2011; Barrett, 2013; Berazneva and Lee, 2013). High food prices affect food access and food availability, but such insecurity is highly conditional on the responses of markets and governments and hence is variable. Berazneva and Lee (2013) show that 14 countries in Africa experienced food riots in 2008 and that they are characterized by higher levels of poverty, restricted food access and availability, are more urbanized, and have more oppressive regimes and stronger civil societies than those countries that did not experience riots. The linkages between food riots and climate change are therefore dependent on responses of multiple private and state actors and it is generally concluded that it is difficult to attribute causality (Barrett, 2013).

Food prices, food access, and food availability are critical elements of human security. There is robust evidence that food security affects basic-needs elements of human security and, in some circumstances, is associated with political stability and climate stresses. But there are complex pathways between climate, food production, and human security and hence this area requires further concentrated research as an area of concern.

in part by observed warming trends in regions. This body of knowledge from across social science disciplines argues that climate change is embedded in and acts on culture in myriad ways. For example, all consumption patterns are culturally embedded and therefore culture influences greenhouse gas emissions. The phenomenon of climate change itself is perceived differently depending on the culture in which it is viewed, with scientific expression representing only one possibility (Norgaard, 2011). Similarly, there are widely different cultural expressions of weather, risk, and the need for adaptation to such hazards (Hulme, 2008; Adger et al., 2013). Therefore, since climate change has consequences for people this emerging body of knowledge shows with *high confidence* that climate change has significant cultural implications (Crate, 2011; Strauss, 2012).

Anthropological analysis of culture focuses on identity, community, and economic activities. There is a growing body of research on how climate and other environmental change affects livelihood activities such as pastoralism, herding, farming, fishing and hunting, and gathering in places where there is significant observed change. Research has documented how rural livelihoods and, therefore, cultural practices have been affected by changes in climate and associated impacts on natural capital. Many anthropological studies suggest that further significant changes in the natural resource base on which many cultures depend would directly affect the cultural core, worldviews, cosmologies, and mythological symbols of indigenous cultures (Crate, 2008; Gregory and Trousdale, 2009; Jacka, 2009). While changing socioeconomic and environmental conditions may constrain existing community coping mechanisms (Rattenbury et al., 2009; West and Hovelsrud, 2010; Quinn et al., 2011), other studies focus on how cultures adapt to significant societal and environmental changes. Many successful examples of the persistence of cultures despite significant upheaval exist throughout history (Nuttall, 2009; Cameron, 2012; Strauss, 2012).

Culture also interacts with adaptation through the way that cultural, local, and individual perceptions affect narratives of risk, resilience, and adaptive capacity. A body of research across disciplines argues that incorporation of cultural understanding of environment, risk, and social practices increases the explanatory power of models of risk (Ifejika Speranza et al., 2008; Jacka, 2009; Adger et al., 2011a). The way in which resource-dependent communities articulate and perceive climate change is often based on how English language terms are translated and understood in the local language (Rudiak-Gould, 2012). Furthermore, information is interpreted through personal life stories and culture (Kuruppu and Liverman, 2011). Local perceptions of what kind of knowledge is trustworthy may in fact lead to questioning of scientific findings (Ingram et al., 2002; Burns et al., 2010; Roncoli et al., 2011). Table 12-2 illustrates different dimensions in which climate change is interpreted and through which human security is affected.

Culturally embedded perceptions of climate change may either facilitate or hinder adaptation with implications for human security (Zamani et al., 2006; Burningham et al., 2008; West and Hovelsrud, 2010; Gómez-Baggethun et al., 2012; Nursey-Bray et al., 2012; Rudiak-Gould, 2012). Scientific information on weather variability and change is framed through cultural practices that can both enable (Dannevig et al., 2012) and constrain (Roncoli, 2006) adaptation. There are a number of anthropological studies that document how some cognitive frames do not perceive a changing climate and hence the concept of climate change itself does not have cultural resonance, whether or not the parameters of climate have been observed (Kuruppu and Liverman, 2011; Lipset, 2011; Sánchez-Cortés and Chavero, 2011; Rudiak-Gould, 2012). Most of these studies conclude that climate policies do not have legitimacy and salience when they do not consider how individual behavior and collective norms are embedded in culture (Stadel, 2008; Jacka, 2009).

There is a significant body of research that analyzes community and collective action for adaptation and generally finds positive outcomes. Many studies conclude that community-led action is effective for reducing risks and building capacity for adaptation (Davidson et al.,

Table 12-2 | Cultural dimensions of climate science, policy, impacts, and extreme events in the context of climate change.

Core climate change dimensions	Cultural dimensions	Role in human security	Sources
Climate science and policy	Framing of climate change in a dominant language Global climate change policy implemented at international scales	How concepts and uncertainties are translated, imported, and incorporated can facilitate or hinder adaptation: *Facilitate adaptation*: available explanatory tools; successful translation of climate change impacts; awareness of culture *Hinder adaptation*: lack of trust in science and in policy; policy not recognizing the connection between nature and culture Policy and decision making that is inclusive of cultural perspectives *increases security*.	Ifejika Speranza et al. (2008); Stadel (2008); Jacka (2009); Green et al. (2010); Osbahr et al. (2010); Schroeder (2010); Gero et al. (2011); Kuruppu and Liverman (2011); Roncoli et al. (2011); Sánchez-Cortés and Chavero (2011); McNeely (2012); Rudiak-Gould (2012)
Impacts of environmental conditions, extreme events, and changing natural resource base	Elements of collective understanding such as: • Worldviews • Coupling of nature–culture • Power relations • Heterogeneity within groups and communities	*Facilitate adaptation*: New technologies; livelihood diversification and flexibility; perceptions of resilience; narratives and history about past changes and current conditions; co-management of resources increases adaptive capacity. *Hinder adaptation*: limitations of local knowledge; lack of awareness and understanding of culture constrains action; knowledge and cultural repertoire limited for responding to new challenges; perceptions of resilience Erosion of cultural core potentially *decreases human security*. Institutional responses and resource management will impact human security either negatively or positively.	Nunn (2000); Davidson et al. (2003); Desta and Coppock (2004); Ford et al. (2006, 2008); Furgal and Seguin (2006); Kesavan and Swaminathan (2006); Zamani et al. (2006); Nyong et al. (2007); Tyler et al. (2007); Angassa and Oba (2008); Burningham et al. (2008); Crate (2008); de Sherbinin et al. (2008); King (2008); Gregory and Trousdale (2009); Jacka (2009); Pearce et al. (2009); Berkes and Armitage (2010); Dumaru (2010); Fazey et al. (2010); Hovelsrud and Smit (2010); Hovelsrud et al. (2010a,b); Kalikoski et al. (2010); Kuhlicke (2010); Lefale (2010); Nielsen and Reenberg (2010); Osbahr et al. (2010); Rybråten and Hovelsrud (2010); Valdivia et al. (2010); West and Hovelsrud (2010); Armitage et al. (2011); Gero et al. (2011); Harries and Penning-Rowsell (2011); Kuruppu and Liverman (2011); Marshall (2011); Onta and Resurrection (2011); Roncoli et al. (2011); Adler et al. (2012); Anik and Khan (2012); Eakin et al. (2012); Ford and Goldhar (2012); Gómez-Baggethun et al. (2012); McNeeley (2012); Nursey-Bray et al. (2012); Rudiak-Gould (2012); Sudmeier-Riuex et al. (2012)
Scientific observations, monitoring, models, projections, scenarios	Local, traditional, and indigenous knowledge through observations and experience	*Facilitate adaptation*: mutual integration of traditional, local, and scientific knowledge; climate projections with local relevance; intergenerational knowledge transfers Local knowledge included in climate policy and decision making *increases human security*. Knowledge not included in adaptation planning *decreases human security*.	Orlove et al. (2000, 2010); Ingram et al. (2002); Tàbara et al. (2003); Alcántara-Ayala et al. (2004); Roncoli (2006); Anderson et al. (2007); Forbes (2007); Nyong et al. (2007); Tyler et al. (2007); Vogel et al. (2007); Catto and Parewick (2008); Marfai et al. (2008); Mercer et al. (2009); Pearce et al. (2009); Burns et al. (2010); Frazier et al. (2010); Gearheard et al. (2010); Hovelsrud and Smit (2010); Marin (2010); Mark et al. (2010); Smit et al. (2010); Flint et al. (2011); Huntington (2011); Kalanda-Joshua et al. (2011); Ravera et al. (2011); Sánchez-Cortés and Chavero (2011); Dannevig et al. (2012); Eira et al. (2013)

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2003; Furgal and Seguin, 2006; Catto and Parewick, 2008; Fazey et al., 2010; Gero et al., 2011; Harries and Penning-Rowsell, 2011; Anik and Khan, 2012; Sudmeier-Riuex et al., 2012; Adler, et al., 2013). Specifically, this literature finds that community participation in risk and vulnerability assessments produces more sustainable solutions (Ardalan et al., 2010; Gero et al., 2011) and that co-management of resources and learning increase adaptive capacity (Ford et al., 2007; Dumaru, 2010; Fazey et al., 2010; Armitage et al., 2011). Much of this literature recognizes, however, the structural barriers to community-led action and limited participation that can hinder effective community adaptation to climate change (Singleton, 2000; Davidson et al., 2003; King, 2008; Ensor and Berger, 2009; Nielsen and Reenberg, 2010; Onta and Resurrection, 2011). Further studies highlight barriers to widespread community responses that result from colonial history (Marino, 2012) and from political and economic globalization (O'Brien et al., 2004; Keskitalo, 2009).

12.3.2. Indigenous Peoples

There are around 400 million indigenous people worldwide (see Glossary for an inclusive definition), living under a wide range of social, economic, and political conditions and locations (Nakashima et al., 2012). Indigenous peoples represent the world's largest reserve of cultural diversity and the majority of languages (Sutherland, 2003). Climate change poses challenges for many indigenous peoples, including challenges to post-colonial power relations, cultural practices, their knowledge systems, and adaptive strategies. For example, the extensive literature on the Arctic shows that changing ice conditions pose risks in terms of access to food and increasingly dangerous travel conditions (Ford et al., 2008, 2009; Hovelsrud et al., 2011; see also Section 28.4.1). Accordingly, there is a strong research tradition on the impacts of climate change in regions with substantial indigenous populations that focuses on indigenous peoples and their attachment to place. Most studies focus on local, traditional, and rural settings (Cameron, 2012) and hence have been argued to create a knowledge gap regarding new urban indigenous populations. Indigenous peoples are often portrayed in the literature as victims of climate change (Salick and Ross, 2009) and as vulnerable to its consequences (ACIA, 2005). However, traditional knowledge is increasingly being combined with scientific understanding to facilitate a better understanding of the dynamic conditions of indigenous peoples (Huntington, 2011; see also Section 12.3.4).

There is *high agreement* that, historically, indigenous peoples have had a high capacity to adapt to variable environmental conditions. This literature also suggests indigenous peoples also have less capacity to cope with rapidly changing socioeconomic conditions and globalization (Tyler et al., 2007; Crate and Nuttall, 2009). Documented challenges for indigenous cultures to adapt to colonization and globalization may reflect resilience and the determination of indigenous peoples to maintain cultures and identities. Furthermore, historical legacies affect the way that indigenous populations adapt to modern challenges: anthropological research has documented clear linkages between historical colonization and the way the way indigenous peoples respond to current climatic changes (Salick and Ross, 2009; Cameron, 2012; Howitt et al., 2012; Marino, 2012).

Most of the literature in this area emphasizes the significant challenge of maintaining cultures, livelihoods, and traditional food sources under the impacts of climate change (Crate and Nuttall, 2009; Rybråten and Hovelsrud, 2010; Lynn et al., 2013). Examples from the literature show that traditional practices are already under pressure from multiple sources, reducing the ability of such practices to enable effective responses to climate variability (Green et al., 2010). Empirical evidence suggests that the efficacy of traditional practices can be eroded when governments relocate communities (Hitchcock, 2009; McNeeley, 2012; Maldonado et al., 2013); if policy and disaster relief creates dependencies (Wenzel, 2009; Fernández-Giménez et al., 2012); in circumstances of inadequate entitlements, rights, and inequality (Shah and Sajitha, 2009; Green et al., 2010; Lynn et al., 2013); and when there are constraints to the transmission of language and knowledge between generations (Forbes, 2007). Some studies show that current indigenous adaptation strategies may not be sufficient to manage the projected climate changes (Wittrock et al., 2011).

Assessments of the cultural implications of climate change for human security illustrate similarities across indigenous peoples. Indigenous peoples have a right to maintain their livelihoods and their connections to homeland and place (Howitt et al., 2012) and it is suggested that the consequences of climate change are challenging this right (Box 12-1; Crate and Nuttall, 2009). Some raise the question whether the Western judicial system can uphold indigenous rights in the face of climate change (Williams, 2012) and that there is a need for justice that facilitates adaptation (Whyte, 2013). In addition, there are uneven societal consequences related to climate change impacts (e.g., use of sea ice: Ford et al., 2008), which add complexity to adaptation in indigenous societies. Heterogeneity within indigenous groups and differentiated exposure to risk has been found in other contexts, for example, in pastoralist groups of the Sahel (Barrett et al., 2001).

Much research on indigenous peoples concludes that lack of involvement in formal, government decision making over resources decreases resilience: the literature recommends further focus on indigenous perceptions of risk and traditional knowledge of change, hazards, and coping strategies and collective responses (Ellemor, 2005; Brown, 2009; Finucane, 2009; Turner and Clifton 2009; Sánchez-Cortés and Chavero, 2011; Maldonado et al., 2013). Though providing economic opportunities, tourism development and industrial activities are particular areas of risk for indigenous peoples when affected populations are not involved in decision making (Petheram et al., 2010). Lack of formal participation in international negotiations may pose risks for indigenous peoples because their perspectives are not heard (Schroeder, 2010). However, there are examples of successful indigenous lobbying and advocacy, as in the case of managing persistent organic pollutants and heavy metals in the Arctic (Selin and Selin, 2008).

12.3.3. Local and Traditional Forms of Knowledge

There is *high agreement* among researchers that involvement of local people and their local, traditional, or indigenous forms of knowledge in decision making is critical for ensuring their security (Ellemor, 2005; Kesavan and Swaminathan, 2006; Burningham et al., 2008; Mercer et al., 2009; Pearce et al., 2009; Anik and Khan, 2012). Such forms of knowledge include categories such as traditional ecological knowledge,

Frequently Asked Questions

FAQ 12.2 | Can lay knowledge of environmental risks help adaptation to climate change?

Lay knowledge about the environment and climate is deeply rooted in history, and encompasses important aspects of human life. Lay knowledge is particularly pertinent in cultures with an intimate relationship between people and the environment. For many indigenous and rural communities, for example, livelihood activities such as herding, hunting, fishing, or farming are directly connected to and dependent on climate and weather conditions. These communities thus have critical knowledge about dealing with environment changes and associated societal conditions. In regions around the world, such knowledge is commonly used in adapting to environmental conditions and is directly relevant to adaptation to climate change.

indigenous science, and ethnoscience (Nakashima and Roué, 2002). Collectively they are defined as "a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations" (Berkes, 2012, p. 7). In addition to reasserting culture, identity, and traditional values, such forms of knowledge are experiential, dynamic, and highly context dependent, developed through interactions with other forms of knowledge (Ford et al., 2006; Orlove et al., 2010; Sánchez-Cortés and Chavero, 2011; Eira et al., 2013).

The conclusion of many anthropological studies in this area is that there is *robust evidence* that mutual integration and co-production of local and traditional and scientific knowledge increase adaptive capacity and reduce vulnerability (Kofinas, 2002; Oberthür et al., 2004; Anderson et al., 2007; Tyler et al., 2007; Vogel et al., 2007; Marfai et al., 2008; West et al., 2008; Frazier et al., 2010; Armitage et al., 2011; Flint et al., 2011; Ravera et al., 2011; Nakashima et al., 2012; Eira et al., 2013). Local and traditional knowledge about historical changes and adaptation strategies are valuable for evaluating contemporary responses to environmental and social change and policy (Orlove et al., 2000; Desta and Coppock, 2004; Angassa and Oba, 2008; Ford et al., 2008; Lefale, 2010; Osbahr et al., 2010; Fernández-Giménez et al., 2012; Eira et al., 2013). Traditional knowledge contributes to mitigating the impact of natural disasters (Rautela, 2005), maintaining domestic biodiversity (Emperaire and Peroni, 2007) and developing sustainable adaptation and mitigation strategies (Nyong et al., 2007; Adler et al., 2013). A study of Borana indigenous pastoralists, for example, documented how loss of technical and organizational practices contributed to progressive land degradation, erosion of social structures, and poverty (Homann et al., 2008). Local and traditional knowledge is also applied in folk forecasting of weather and has been shown to be mutually reinforcing with scientific forecasts of weather at different time scales (Orlove et al., 2000; Nyong et al., 2007; Tyler et al., 2007; Gearheard et al., 2010; Hovelsrud and Smit, 2010).

Despite recognition in studies of the value of local and traditional knowledge, such knowledge is most often not included in adaptation planning (Tàbara et al., 2003; King et al., 2007; Ifejika Speranza et al., 2008; Huntington, 2011). There are many challenges in managing, utilizing, acknowledging, and incorporating local and traditional knowledge into adaptation practices (Huntington, 2011). Such knowledge is often generated and collected through participatory approaches, an approach that may not be sufficient because of the cultural and social dynamics of power and interpretation (Roncoli et al., 2011). Local and traditional knowledge itself may have its limits. Some studies suggest that local or traditional knowledge may not be sufficient to provide the proper response to unexpected or infrequent risks or events (Nunn, 2000; Burningham et al., 2008; Kuhlicke, 2010).

There is also concern, documented in many anthropological studies, that indigenous and traditional knowledge is itself under threat. If local or traditional knowledge is perceived to be less reliable because of changing environmental conditions (Ingram et al., 2002; Ford et al., 2006) or because of extreme or new events that are beyond the current local knowledge and cultural repertoire (Valdivia et al., 2010; Hovelsrud et al., 2010a), then community vulnerability, and the vulnerability of local or traditional knowledge itself, may increase (Kalanda-Joshua et al., 2011). New conditions may require new knowledge to facilitate and maintain flexibility and improve livelihoods (see also Homann et al., 2008). Kesavan and Swaminathan (2006) documented how societal and environmental conditions have changed to the point that local knowledge is supplemented with new technologies and new knowledge in coastal communities in India. A study in the Himalayas found that erosion of traditional knowledge occurs through government regulations of traditional building materials and practices (Rautela, 2005). The social cohesion embedded in such practices is weakened because of a move toward concrete construction which changes the reliance on and usefulness of traditional knowledge about wood as a building material (Rautela, 2005).

12.4. Migration and Mobility Dimensions of Human Security

12.4.1. Impacts of Climate Change on Displacement, Migration, and Mobility

12.4.1.1. Nature of Evidence on Climate Change and Migration

This section details how some existing migration systems may be significantly disrupted by impacts of climate change in a number of important dimensions. This finding comes from a very significant new body of observational and theoretical research in the past 5 years, as the migration and mobility dimensions of the impacts of climate change and the central role of mobility in adaptation have become apparent

(Afifi and Jäger, 2010; Foresight, 2011; Piguet et al., 2011). As with other elements of human security, the dynamics of the interaction of mobility with climate change are multifaceted and direct causation is difficult to establish.

The major findings of this emerging science demonstrate the multiple drivers of migration; show the role of displacement of populations from extreme weather events; and highlight the governance challenges of displaced peoples and the challenges of migration for urban sustainability (Black et al., 2011a,c; Foresight, 2011; Parnell and Walawege, 2011; Seto, 2011; White, G., 2011; Geddes et al., 2012). Studies have derived these findings through multiple methods and lines of evidence including statistical inference to explain observed migration patterns using climate or related impacts as independent variables; sample surveys of migrant motivations and behavior; modeling techniques; and historical analogs (McLeman and Hunter, 2010; Piguet, 2010; Warner, 2011; Oswald Spring et al., 2013; Warner and Afifi, 2013).

Migration in this chapter is defined in terms of temporal and spatial characteristics: it is a permanent or semi-permanent move by a person of at least one year that involves crossing an administrative, but not necessarily a national, border (Brown and Bean, 2005). Permanent migration, as well as temporary and seasonal migration, are prevalent in every part of the world, and are driven by economic and other imperatives. The most significant contemporary overall trend in migration continues to be major movements of people from rural to urban settlements. The proportion of the global population that is urban has risen from 10% in 1900 to more than 50% in 2009 and is projected to reach 59% by 2030 (Grimm et al., 2008). Around 80% of all migration is presently within countries (UNDP, 2009). Existing global migration trends mapped onto ecological zones by de Sherbinin et al. (2012) show that the past 4 decades have seen out-migration from mountain regions and from drylands. Net migration to coastal zones is estimated as having been more than 70 million people in the 1990–2000 census period.

12.4.1.2. Potential Pathways from Climate Change to Migration

Extreme weather events provide the most direct pathway from climate change to migration. It is widely established that extreme weather events displace populations in the short term because of their loss of place of residence or economic disruption. Only a proportion of displacement leads to more permanent migration (Foresight, 2011; Hallegatte, 2012). Much of the literature, such as reviewed in the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX), concludes that an increasing incidence and changing intensity of extreme weather events due to climate change will lead directly to the risk of increased levels of displacement.

The evidence on displacement as a result of weather-related events suggests that most displaced people attempt to return to their original residence and rebuild as soon as practical. The Pakistan floods of 2010, for example, caused primarily localized displacement for large numbers of people across a wide area (Gaurav et al., 2011), rather than longer-distance migration. Structural economic causes of social vulnerability may determine whether temporary displacement turns into permanent migration. In New Orleans, after Hurricane Katrina, for example, economically disadvantaged populations were displaced in the immediate aftermath and most have not returned (Myers et al., 2008; Mutter, 2010). Fussell et al. (2010) found that 14 months after the event, African American residents returned more slowly, because they had suffered greater housing damage. Studies conclude that displacement affected human security through housing, economic, and health outcomes and that these have perpetuated the initial impact into a chronic syndrome of insecurity (Adams et al., 2009; Hori and Shafer, 2010). Furthermore, there are well-documented gender differences in displacement from extreme events, especially when women lose their social networks or their social capital, and women are often affected by adverse mental health outcomes in situations of displacement (Tunstall et al., 2006; Oswald Spring, 2008; Hunter and David, 2011).

Therefore, extreme weather events are not necessarily associated with displacement and can also be associated with immobility or in-migration. Changing economic structures can shape the ability of affected populations to cope with extreme weather without being displaced. While the poorest households in Honduras suffered greatest losses due to the impacts of Hurricane Mitch in 1990 (Glantz and Jamison, 2000; McLeman and Hunter, 2010; McSweeney and Coomes, 2011), they were found to be less vulnerable to storms a decade later due to changes in land tenure and better early warning systems (Villagrán de León, 2009). Paul (2005) found that there was little displacement in Bangladesh following floods and that residents perceived an influx of migrants due to the reconstruction.

It is well established in demography that while migration is a common strategy to deal with livelihood risk, movement is costly and disruptive and hence may be used only as an adaptation of last resort (McLeman, 2009). Hurlimann and Dolnicar (2011) showed for eight Australian settlements experiencing long-term drought that relocation and migration was perceived to be the least desirable adaptation. Marshall et al. (2012) similarly showed that place attachment dominated decision making and reluctance to undertake relocation of farming communities. Haug (2002) showed that pastoralists displaced due to drought in Sudan in the 1990s attempted to return to their previous settlements after the drought, notwithstanding conflict and other factors. McLeman and Hunter (2010) reviewed historical cases of displacement migration and concluded that non-migration or rapid return significantly outweighs permanent migration following hurricane impacts in the Caribbean, Dust Bowl migration in the 1930s USA, or dry season migration in the West African Sahel.

A further strand of evidence shows social differentiation in access to the resources necessary to migrate influences migration outcomes (Renaud et al., 2011; Black et al., 2013). Vulnerability is inversely correlated with mobility, leading to those being most exposed and vulnerable to the impacts of climate change having the least capability to migrate (Figure 12-1). Therefore, climate change risks can be significant when they reduce and constrain opportunities to move (Black et al., 2013). Alternatively, the most vulnerable households are able to use migration to cope with environmental stress, but their migration is an emergency response that creates conditions of debt and increased vulnerability, rather than reducing them (Warner and Afifi, 2013). Table 12-3 summarizes studies on the migration outcomes of weather extremes and long-term environmental change. It shows that some events lead to increased

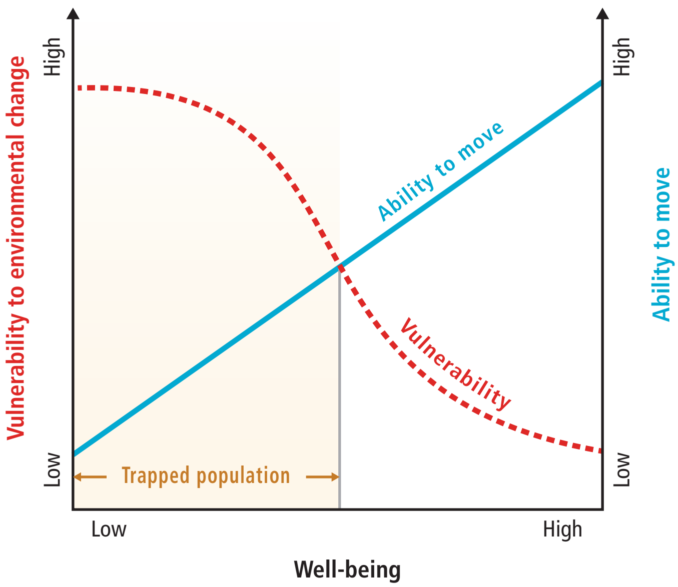

Figure 12-1 | Relationship between vulnerability to environmental change and mobility showing that populations most exposed and vulnerable to the impacts of climate change may have least ability to migrate (adapted from Foresight, 2011; Black et al., 2013).

displacement of populations, while others lead to reduced mobility. Table 12-3 also demonstrates that, in many circumstances, members of a population will display differentiated migration outcomes on the basis of ethnicity, wealth, or gender (Elliot and Pais, 2006; Gray and Mueller, 2012; Upton, 2012).

There is some evidence that climate changes, through impacts on productivity, can lead to reductions in migration flows. Studies in Table 12-3 highlight that some longer distance migration is reduced by drought in pastoral systems (Findley, 1994; van der Geest, 2011; Sánchez et al., 2013). Drought was also found to reduce migration in other systems. Henry et al. (2004) confirmed in a multiyear study of Burkina Faso that the movement to other rural areas increased in dry years, but long-distance or international migration was limited to years of high agricultural productivity. Pioneer migration to new destinations, long distance migration, and international migration all require significant human and financial capital and hence are restricted to wealthier populations or to time periods where the household has sufficient resources. However, in some contexts drought can lead to increased migration—often short-term and short-distance migration. Kniveton et al. (2011, 2012) modeled migration movements from the 1980s in Burkina Faso and project that future scenarios of decreased rainfall would increase rates of out-migration from rural areas.

Whether or not negative environmental change influences the decision to migrate, migrant populations may be exposed to more hazardous climatic conditions in their new destinations (Black et al., 2011b). There is some evidence that new migrants are more at risk in destination areas such as cities. Low-income migrants, as well as being socially excluded, cluster in high-density areas that are often highly exposed to flooding and landslides, with these risks increasing with climate change (Chatterjee, 2010; Fox and Beall, 2012; McMichael et al., 2012). Migrants in Buenos Aires, Lagos, Mumbai, and Dakar (Chatterjee, 2010; World Bank, 2010; Mehrotra et al., 2011) more often live in more hazardous locations than long-term residents. In Dakar, 40% of new migrants in the decade until 2008 resided in areas with high flood risk (World Bank, 2010). Wang et al. (2012) found that migrants had less knowledge about typhoon risks in Shanghai. Tompkins et al. (2009) showed that new migrants in the Cayman Islands are most vulnerable to tropical cyclones as they are least likely to prepare for cyclones, more likely to live in locations with high exposure to cyclone impacts, and interact mostly with expatriates without previous cyclone experience. There is no established evidence that rapid urbanization itself is a source of conflict: Buhaug and Urdal (2013) test hypotheses on social disorder and population growth in 55 cities in Africa and find that rapid growth of city populations does not drive urban unrest.

12.4.1.3. Migration Trends and Long-Term Climate Change

Long-term environmental change, sea level rise, coastal erosion, and loss of agricultural productivity (Table 12-3) will have a significant impact

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Frequently Asked Questions

FAQ 12.3 | How many people could be displaced as a result of climate change?

Displacement is the movement of people from their place of residence, and can occur when extreme weather events, such as flood and drought, make areas temporarily uninhabitable. Major extreme weather events have in the past led to significant temporary population displacement, and changes in the incidence of extreme events will amplify the challenges and risks of such displacement. However, many vulnerable groups do not have the resources to be able to migrate from areas exposed to the risks from extreme events. There are no robust global estimates of future displacement, but there is significant evidence that planning and increased mobility can reduce the human security costs of displacement from extreme weather events. Climate changes in rural areas could amplify migration to urban centers. However, environmental conditions and altered ecosystem services are few among the many reasons why people migrate. So while climate change impacts will play a role in these decisions in the future, given the complex motivations for all migration decisions, it is difficult to categorize any individual as a climate migrant (Section 12.4).

Table 12-3 | Empirical evidence on observed or projected mobility outcomes (migration, immobility, or displacement) associated with weather-related extremes or impacts of longer-term climate change.

Type of impact or extreme	Change in migration trend or flow	Region	Impact on migration, by type of short-term event and long-term change	Source
Drought and land degradation	Evidence for increased mobility or increased displacement	Ethiopia	Outmigration of household heads due to drought-related famine. Different coping strategies lead to variations in the timing of migration.	Meze-Hausken (2000)
		Mexico	At the state level, a reduction in crop yields is associated with an increase in international migration to the United States.	Feng et al. (2010)
		Western Sahara	Environmental factors influenced decisions to migrate internationally from refugee camps.	Gila et al. (2011)
		Kenya	Households farming high-quality soil are less likely to migrate, especially for temporary labor; soil degradation therefore causes increased outmigration.	Gray (2011)
		India	Temporary migration is identified as "the most important" coping strategy in times of drought in rural villages.	Jülich (2011)
		Canada	Higher population loss was associated with settlements containing areas of poorer quality agricultural soils during droughts of 1930s.	McLeman and Ploeger (2012)
		Guatemala	Migrants to the expanding agricultural frontier commonly attributed their outmigration to soil degradation.	López-Carr (2012)
		Sahel	In three case regions, the pressure to migrate had significantly increased since the 1970s, with response to persistent droughts identified as a factor.	Scheffran et al. (2012b,d)
		Burkina Faso	Drier region populations were more likely to engage in rural–rural migration, both temporary and permanent, than people from regions with more rainfall. Rainfall deficits have different impacts depending on the duration and distance of the migration.	Henry et al. (2004)
		Burkina Faso[a]	Simulated scenarios of dry climate increase migration fluxes compared to wet scenarios. Highest international migrant flows are shown with the dry climate scenarios.	Kniveton et al. (2011)
	Evidence for decreased mobility	Mali	Reduced international migration occurred during the 1980s drought concurrently with an increase in localized cyclical migration.	Findley (1994)
		Nepal	Deforestation, population pressure, and agricultural decline leads to local mobility, especially among women, but no increases in internal or international migration.	Massey et al. (2010); Bohra-Mishra and Massey (2011)
		Uganda	High soil quality marginally increases migration, especially permanent non-labor migration; therefore soil degradation reduces outmigration.	Gray (2011)
	Evidence for socially differentiated mobility outcomes	United States	Dustbowl migrants from Oklahoma to California in the 1930s had different social and economic capital endowments from those who stayed within state.	McLeman and Smit (2006)
		Ecuador	Influence of natural capital on migration differed between men and women. Access to land facilitates migration in men; women are less likely to migrate from environmentally degraded areas.	Gray (2010)
		Ethiopia	Male migration increases with drought. However, marriage-related moves by women decrease with drought.	Gray and Mueller (2012)
		Burkina Faso	Labor migration became a key off-farm livelihood strategy after droughts in the 1970s for groups dependent on rain-fed agriculture.	Nielsen and Reenberg (2010)
		Mongolia	Diversity was seen in herders' mobility strategies in response to climate change. For a minority, responses entailed greater overall annual mobility. Other herding households experienced significant reductions in mobility.	Upton (2012)
Flooding	Evidence for increased mobility or increased displacement	United States	Ten counties and parishes in Louisiana, of the 77 impacted counties, experienced 82% of the total population increase in the year following Hurricane Katrina.	Frey and Singer (2006)
		Vietnam	Cumulative impacts of seasonal flooding increase outmigration rates in the Mekong Delta.	Dun (2011)
		Bangladesh	22% of households affected by tidal-surge floods, and 16% affected by riverbank erosion, moved to urban areas.	Foresight (2011)
	Evidence for decreased mobility or trapped populations	Bangladesh	No outmigration was detected after 2004 tornado in Bangladesh as a result of the effective distribution of disaster aid.	Paul (2005)
		Senegal	More than 40% of new migrant populations located in high risk flood zones in Dakar.	Foresight (2011)
	Evidence for socially differentiated mobility outcomes	United States	Emergency evacuation responses and return migration after Hurricane Katrina were highly differentiated by income, race, class, and ethnicity.	Elliott and Pais (2006); Falk et al. (2006); Landry et al. (2007)
		Bangladesh	Wide variation seen among groups in attitudes toward, and capabilities for, migration as an adaptation to the impact of cyclone Aila.	Kartiki (2011)

Continued next page →

on migration flows (Lilleor and Van den Broeck, 2011). The evidence in this area comes from simulation studies of future migration flows and permanent displacement. Barbieri et al. (2010) estimated emigration rates in Brazil from affected rural areas and found that de-population occurs with relatively modest rates of warming. In their scenarios the biggest increase in migration comes from productive agricultural areas that support a large labor force. In a separate study, Mendelsohn et al. (2007) concluded that in dryland Brazil urban migration is *very likely*

Table 12-3 (continued)

Type of impact or extreme	Change in migration trend or flow	Region	Impact on migration, by type of short-term event and long-term change	Source
Sea level rise	Evidence for increased mobility or increased displacement	United States	Relative sea level rise caused island depopulation in Maryland. Final abandonment was a result of the population falling below the threshold required to support local services.	Arenstam Gibbons and Nicholls (2006)
			Coastal villages in Alaska are affected by sea level rise and coastal erosion to the point where resettlement is the only viable adaptation.	Bronen (2010); Oliver-Smith (2011); Marino (2012)
		United States[a]	The impact of future sea level rise is projected to extend beyond the inundated counties through migration networks that link inland and coastal areas and their populations.	Curtis and Schneider (2011)
		Vanuatu	Contemporary example of whole village displacement was associated with inundation, both from sea level rise and tectonic movement on Torres Islands.	Ballu et al. (2011)
		Papua New Guinea	Communities on Bougainville are considering resettlement to the main island due to coastal erosion, land loss, saltwater inundation, and food insecurity.	Oliver-Smith (2011)
	Evidence for decreased mobility or lower migration	Tuvalu	On the island of Funafuti, surveyed residents emphasize place attachment as reasons for not migrating, and do not cite climate change as a reason to migrate.	Mortreux and Barnett (2009)

Note: [a]Study based on simulations or projections.

due to agricultural income loss. Longer term environmental change caused by climate change also amplifies existing trends such as rural to urban migration, though results diverge on the importance of climate change and resource scarcity in driving such trends. Modelling studies with future projections on Mexico-USA migration rates (Feng et al., 2009) and on Brazilian internal migration (Barbieri et al., 2010) show that projections of drying increase emigration in established migration routes and de-population of rural areas (Oswald Spring et al., 2013). Barrios et al. (2006) showed that observed rainfall declines in areas of sub-Saharan Africa explain part of the differences in urbanization rates across countries, with periods of rainfall decline increasing urbanization in sub-Saharan Africa, but the urbanization is also explained by simultaneous economic liberalization and policy change.

Sea level changes have been projected to lead to permanent displacements as coastal areas become uninhabitable. Curtis and Schneider (2011), for example, project 12 million people to be displaced by sea level rise by 2030 in four major coastal areas in the USA. Nicholls et al. (2011) estimate permanent displacements based on potential sea level changes until 2100 (see Section 5.5.7). A 0.5 m sea level change implies a *likely* land loss of 0.877 million km^2 by 2100, displacing 72 million people, with no adaptation investment; with a 2.0 m sea level change, 1.789 million km^2 would be lost, displacing 187 million people, or 2.4% of global population, mostly in Asia. If governments undertook adaptation investments in all coasts (e.g., building protective dikes), then the study suggests very low levels of people displaced under the 0.5 m scenario and a population of less than half a million displaced under the 2.0 m sea level rise scenario (Nicholls et al., 2011). Hallegatte et al. (2011) and Seto (2011) show that such protection measures are *very likely* to be implemented because of the high cost of not investing in protecting urban land and infrastructure, especially for major urban centers.

Even in areas under threat from long-term climate change and sea level rise, observations show that populations at risk do not always choose to migrate. For example, a series of studies have sought to explain population stability in low-lying island nations. Mortreux and Barnett (2009) found that migration from Tuvalu was not driven by perceptions of climate change and that, despite forecasts that the island could become uninhabitable, residents have remained for reasons of culture and identity. Shen and Gemenne (2011) concur that both Tuvalu residents and migrants from Tuvalu did not cite climate change as a reason for the migration that occurs. Similarly, in the Peruvian Andes, Adams and Adger (2013) found that cultural ecosystem services and place attachment shape decisions not to migrate and hence populations persist despite difficult environmental conditions. However, these studies also find that environmental risks directly affect perceptions of well-being, cultural integrity, and economic opportunities. They conclude that the impacts of climate change may be a more significant driver of migration in the future.

12.4.2. Migration as an Adaptation to Climate Change Impacts

Migration is a widely used adaptation strategy that reduces risks in highly vulnerable places, as demonstrated by a wide range of studies. Research drawing on experience of migration policy concludes that a greater emphasis on mobility within adaptation policies would be

Frequently Asked Questions

FAQ 12.4 | What role does migration play in adaptation to climate change, particularly in vulnerable regions?

Moving from one place to another is a fundamental way humans respond to challenging conditions. Migration patterns everywhere are primarily driven by economic factors: the dominant migration system in the world has been movement from rural to urban areas within countries as people seek more favorable work and living conditions.

Box 12-4 | Evidence on the Existence of Environmental Migrants and International Policy for Their Protection

There is widespread agreement in the scientific and legal literature that the use of the term climate refugee is scientifically and legally problematic (Tacoli, 2009; Piguet, 2010; Black et al., 2011a; Gemenne, 2011; Jakobeit and Methmann, 2012; Bettini, 2013; Piguet, 2013). McAdam calls the concept "erroneous as a matter of law and conceptually inaccurate" (McAdam, 2011, p. 102). The reasons are threefold. First, most migration and climate studies point to the environment as triggers and not causes for migration decisions. Second, some studies focus on the negative geo-political implications of changing the Geneva Convention on refugees to include environmental migrants as well as the lack of global instruments to handle internal displaced peoples or international migrants (Martin, 2009; Cournil, 2011). Third, many Small Island States are reluctant themselves to have their international migrants designated as being victims of climate change (McNamara and Gibson, 2009; Farbotko, 2010; Barnett and O'Neill, 2012; Farbotko and Lazrus, 2012).

The arguments put forward for a specific legal instrument to deal with migrants who have been displaced as a direct result of climate change impacts include issues of rights, given such migration is imposed and involuntary (Bates, 2002; Bell, 2004); and the particular status of Small Island States where displacement could affect sovereignty (Biermann and Boas, 2008; Owens, 2008; Williams, 2008). For international displacement and migration, there is a growing literature on practical adaptation and action: the existence of governance mechanisms to improve handling of currently displaced people, and the optimal design of such mechanisms in the future (e.g., Bryavan and Rajan, 2006; Biermann and Boas, 2008; Williams, 2008; Docherty and Giannini, 2009; Martin, 2009; McAdam, 2011). This literature focuses on strategies for adaptation, mitigation, and resilience building, and concludes that significant adaptation may be required to protect and to empower internally or international migrants triggered by climate change.

effective when undertaken in a sensitive manner (Bardsley and Hugo, 2010; Barnett and Webber, 2010; Warner, 2010; Gemenne, 2011). This emerging literature shows that migration can be promoted to reduce risk successfully, not least through remittance flows between sending and destination areas (Deshingker, 2012; Fox and Beall, 2012; Martin, 2012). The prospect of migration as an effective adaptation is recognized through its inclusion in the Cancun Accord of the UN Framework Convention on Climate Change (Warner, 2012).

Various governments are presently engaged in planning to move settlements as part of adaptation strategies, either because of the assessment of new risks or to justify existing resettlement programs (de Sherbinin et al., 2011; Biermann, 2012). Scientific literature on these policies most often portrays resettlement as a failure of adaptation and a policy of last resort (Barnett and Webber, 2010; Fernando et al., 2010; Hugo, 2011). Most practice to date, learning from other resettlement programs, demonstrates negative social outcomes for those resettled, often analyzed as breaches in individual human rights (Bronen, 2011; Johnson, 2012; Arnall, 2013). There are some documented examples of settlements that are already planning for their own relocation, such as five indigenous communities in Alaska that have experienced increased erosion, loss of sea ice cover, and flooding over the past decades (Bronen, 2010). These settlements have undertaken planning for relocation and have received government funding for these processes. Bronen (2010) and Bronen and Chapin (2013) conclude that while the relocations are feasible, there are significant perceptions of cultural loss and related studies report psychological stress and community dislocation (Cunsolo-Wilcox et al., 2012, 2013). The studies argue that legitimacy and success depend on incorporating cultural and psychological factors in the planning processes (Bronen and Chapin, 2013). There is significant resistance to relocation, even where such options are well planned and have robust justifications, as demonstrated by Marino (2012) for relocation in Alaska.

12.5. Climate Change and Armed Conflict

12.5.1. Climate Change as a Cause of Conflict

In the past decade there has been a marked increase in research investigating the relationship between climate change and violent and armed conflict. This section assesses the full spectrum of research using diverse methods and data to understand the relationship between climate change and armed conflict. Chapter 19 provides a more detailed assessment of those studies that seek to quantify the influence of climate factors on violence of all kinds, including personal violence. Chapter 19 defines the influence of climate impacts on violence to be an emergent risk and a new focus of research. In this chapter, armed conflicts are defined as those conflicts that involve more than 25 battle-related deaths in a year. This can include interstate conflicts, intrastate conflicts that involve governments, non-state conflicts in which governments are not directly involved, and one-sided conflicts involving organized violence against civilians (Themnér and Wallensteen, 2012).

There is a specific research field that explores the relationship between large-scale disruptions in climate and the collapse of past empires.

Frequently Asked Questions

FAQ 12.5 | Will climate change cause war between countries?

Climate change has the potential to increase rivalry between countries over shared resources. For example, there is concern about rivalry over changing access to the resources in the Arctic and in transboundary river basins. Climate changes represent a challenge to the effectiveness of the diverse institutions that already exist to manage relations over these resources. However, there is high scientific agreement that this increased rivalry is unlikely to lead directly to warfare between states. The evidence to date shows that the nature of resources such as transboundary water and a range of conflict resolution institutions have been able to resolve rivalries in ways that avoid violent conflict.

Relationships are explored using statistical analysis and data derived from archaeological and other historical records. For example, the timing of the collapse of the Khmer empire in the Mekong basin in the early 15th century corresponds to an unusually severe prolonged drought (Buckley et al., 2010). DeMenocal (2001) summarizes evidence that suggests that major changes in weather patterns coincided with the collapse of several previously powerful civilizations, including the Anasazi, the Akkadian, Classic Maya, Mochica, and Tiwanaku empires. Other historical reference points of the interaction of climate with society emerge from analysis of the Little Ice Age. Some studies show that the Little Ice Age in the mid-17th century was associated with more cases of political upheaval and warfare than in any other period (Parker, 2008; Zhang et al., 2011), including in Europe (Tol and Wagner, 2010), China (Brook, 2010), and the Ottoman empire (White, S., 2011). These studies all show that climate change can exacerbate major political changes given certain social conditions, including a predominance of subsistence producers, conflict over territory, and autocratic systems of government with limited power in peripheral regions. The precise causal pathways that link these changes in climate to changes in civilizations are not well understood due to data limitations. Therefore, it should be noted that these findings from historical antecedents are not directly transferable to the contemporary globalized world. The literature urges caution in concluding that mean future changes in climate will lead to large-scale political collapse (Butzer, 2012).

Most of the research on the connections between climate change and armed conflict focuses on the connections between climate variability and intrastate conflicts in the modern era. For the most part, this research examines rainfall or temperature variability as proxies for the kinds of longer-term changes that might occur due to climate change. Several studies examine the relationship between short-term warming and armed conflict (Burke et al., 2009; Buhaug 2010; Koubi et al., 2012; O'Loughlin et al., 2012; Theisen et al., 2012). Some of these find a weak relationship, some find no relationship, and collectively the research does not conclude that there is a strong positive relationship between warming and armed conflict (Theisen et al., 2013).

The large majority of studies focuses on Africa and use satellite-enhanced rainfall data collected since 1980. A global study by Hsiang et al. (2011) considers changes in climate over multiple years, and finds that since 1950 and in countries that are affected by El Niño-Southern Oscillation (ENSO) the risk of war within countries rises during an ENSO period. This study is supported by some studies that find associations between deviations in rainfall and civil war (Miguel et al., 2004; Hendrix and Glaser, 2007; Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012), but contradicted by others that find no significant association between droughts and floods and civil war (Buhaug, 2010; Buhaug and Theisen, 2012; Koubi et al., 2012; Slettebak, 2012; Theisen et al., 2013). There is *high agreement* that in the specific circumstances where other risk factors are extremely low (such as where per capita incomes are high, and states are effective and consistent), the impact of changes in climate on armed conflict is negligible (Bernauer et al., 2012; Koubi et al., 2012; Scheffran et al., 2012a; Theisen et al., 2013).

A growing body of research examines the connections between climate variability and non-state conflicts. There is some agreement that either increased rainfall or decreased rainfall in resource-dependent economies enhances the risk of localized violent conflict, particularly in pastoral societies in Africa (Benjaminsen and Ba, 2009; Benjaminsen et al., 2009; Adano et al., 2012; Butler and Gates, 2012; Fjelde and von Uexkull, 2012; Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012; Theisen, 2012). In all such cases, the presence of institutions that are able to peacefully manage conflict are highlighted as the critical factor in mediating such risks (Gausset, 2005; Hidalgo et al., 2010; Adano et al., 2012; Benjaminsen et al., 2012; Butler and Gates, 2012; O'Loughlin et al., 2012; Theisen, 2012).

In response to the challenges of finding direct associations between changes in climate and violence, some research has examined the effects of changes in climate on factors that are known to increase the risk of civil war (Bergholt and Lujala, 2012; Koubi et al., 2012). Civil war has been studied extensively using quantitative and qualitative techniques, and there is *high agreement* about factors that increase the risk of civil war, namely a recent history of civil violence, low levels of per capita income, low rates of economic growth, economic shocks, inconsistent political institutions, and the existence of conflict in neighboring countries (Miguel et al., 2004; Weede, 2004; Hegre and Sambanis, 2006; Dixon, 2009; Blattman and Miguel, 2010; Brückner and Ciccone, 2010). Nevertheless, almost all studies note the need for convincing theories that explain these associations.

Many of the factors that increase the risk of civil war and other armed conflicts are sensitive to climate change. For example, Chapter 10 shows that climate change will slow rates of economic growth and impede efforts to grow per capita incomes in some low-income countries, particularly in Africa where the risk of conflict is highest (Mendelsohn

Box 12-5 | Climate and the Multiple Causes of Conflict in Darfur

Climate variability or climate change is popularly reported to be significant causes of the mass killing in the Darfur region that began in 2003 (see Mazo, 2009). Five detailed studies dispute the identification of the Darfur conflict as being primarily caused by climate change (Kevane and Gray, 2008; Brown, 2010; Hagen and Kaiser, 2011; Sunga, 2011; Verhoeven, 2011). They find that the violence in Darfur has multiple causes, notably:

- The legacy of past violence, which established groups that had a history of violent action and a supply of weapons
- Manipulation of ethnic divisions by elites in Khartoum
- Weakening of traditional conflict resolution mechanisms through government policies and as a consequence of famines
- Systematic exclusion of local groups from political processes, including of the Fur, Masalit, and Zaghawa ethnic groups
- Limited economic development and inadequate provision of public services and social protection, stemming from governance and policy failures, political instability, and misuse of official development assistance.

All studies of this conflict agree that it is not possible to isolate any of these specific causes as being most influential (Kevane and Gray, 2008; Hagen and Kaiser, 2011; Sunga, 2011; Verhoeven, 2011). Most authors identify government practices as being far more influential drivers than climate variability, noting also that similar changes in climate did not stimulate conflicts of the same magnitude in neighboring regions, and that in the past people in Darfur were able to cope with climate variability in ways that avoided large-scale violence.

et al., 2000, 2006, Stern, 2007, Eboli et al., 2010). Extreme events, which may become more intense due to climate change, can also produce economic shocks (Bergholt and Lujala, 2012; Hallegatte, 2012; Adam, 2013), although the direct association between disasters and armed conflict is contested (Pelling and Dill, 2010; Bergholt and Lujala, 2012; Slettebak, 2012). Studies have inferred that climate change can undermine the consistency of institutions that provide public goods (Barnett and Adger, 2007; Scheffran et al., 2012b) and hence weaken states and increase conflict risks. However, there is some evidence that, under certain circumstances, disasters can provide critical opportunities to build peace in conflict settings and to improve governance institutions (Kingsbury, 2007; Olson and Gawronski, 2010; Bruckner and Ciccone, 2011).

In summary, there is justifiable common concern that climate change or changes in climate variability increase the risk of armed conflict in certain circumstances (Bernauer et al., 2012; Gleditsch, 2012; Scheffran et al., 2012c; Hsiang et al., 2013), even if the strength of the effect is uncertain. This concern is justified given robust knowledge of the factors that increase the risk of civil wars, and medium evidence that some of these factors are sensitive to climate change.

There is also general agreement in the literature that there is a need for theories and data that explain the processes that lead from changes in climate to violence—for example, on how formal and informal institutions help avoid violent outcomes (Barnett and Adger, 2007; Scheffran and Battaglini, 2011; Buhaug and Theisen, 2012, Gleditsch, 2012; Murtinho and Hayes, 2012). Confident statements about the effects of future changes in climate on armed conflict are not possible given the absence of generally supported theories and evidence about causality (see Box 12-5).

12.5.2. Conflict and Insecurity Associated with Climate Policy Responses

Research is beginning to show that climate change mitigation and adaptation actions can increase the risk of armed conflict, as well as compound vulnerabilities in certain populations (Bumpus and Liverman, 2008; Adger and Barnett, 2009; Webersik, 2010; Fairhead et al., 2012; Marino and Ribot, 2012; Steinbruner et al., 2012). This is based on robust evidence that violent political struggles occur over the distribution of benefits from natural resources (Peluso and Watts, 2001). Hence, in circumstances where property rights and conflict management institutions are ineffective or illegitimate, efforts to mitigate or adapt to climate change that change the distribution of access to resources have the potential to create and aggravate conflict.

Actions taken in response to climate change can aggravate existing significant inequalities or grievances over resources (Marino and Ribot, 2012), limit access to land and other resources required to maintain livelihoods, or otherwise undermine critical aspects of human security (Bumpus and Liverman, 2008; Fairhead et al., 2012). Maladaptation or greenhouse gas mitigation efforts at odds with local priorities and property rights may increase the risk of conflict in populations, particularly where institutions governing access to property are weak, or favor one group over another (Barnett and O'Neill, 2010; Butler and Gates, 2012; McEvoy and Wilder, 2012). Research on the rapid expansion of biofuels production connects land grabbing, land dispossession, and social conflict (Borras et al., 2010; Dauverge and Neville, 2010; Molony and Smith, 2010; Vermeulen and Cotula, 2010). One study has identified possible links between increased biofuels production, food price spikes, and social instability such as riots (Johnstone and Mazo, 2011).

Provision of financial resources in payment for ecosystem services projects, such as are associated with Reduced Emissions from Deforestation and Forest Degradation (REDD), has the potential to stimulate conflict over resources and property rights (Melick, 2010). For example, efforts to ensure "REDD readiness" in Tanzania (Beymer-Farris and Bassett, 2012, 2013; Burgess et al., 2013) and the Congo basin (Brown et al., 2011) have been contested, and placed communities in conflict with conservationists and governments. Eriksen and Lind (2009) similarly find that climate change adaptation interventions in Kenya have aggravated surrounding conflicts.

Climate change mitigation will increase demand for deployment of less carbon-intensive forms of energy, including hydropower, some of which have historically resulted in social conflict and human insecurity (e.g., because of forced resettlement), and this is a basis for concern about increased violence and insecurity in the future (Conca, 2005; McDonald-Wilmsen and Webber, 2010; De Sherbinin et al., 2011). Other research points to an increased use of nuclear power increasing the threat of nuclear proliferation or incidents of nuclear terrorism (Socolow and Glaser, 2009, Steinbruner et al., 2012). Climate policy responses also have the potential to reduce conflict in various ways, as explained further in Section 12.5.4.

12.5.3. Violent Conflict and Vulnerability to Climate Change

Many of the capacities required to adapt to climate change are threatened by ongoing or recent armed conflict (Barnett, 2006; Brklacich et al., 2010). There is a strong body of evidence from development studies and political science that violent conflict undermines human security and the capacity of individuals, communities, and states to cope with

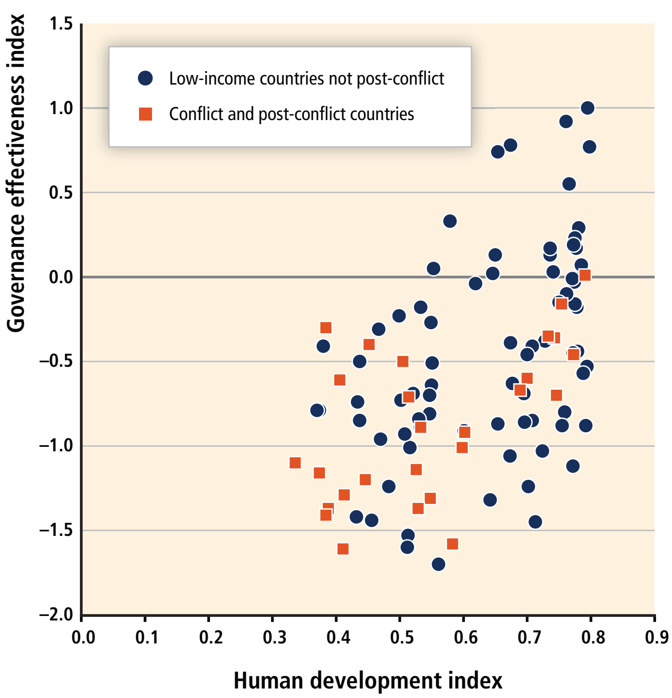


Figure 12-2 | Conflict and post-conflict societies exhibit low levels of governance and human development. Data based on UNDP Human Development Index and World Bank index on governance effectiveness (adapted from Adger, 2010).

changes (Stewart and Fitzgerald, 2001; Blattman and Miguel, 2010). These observations suggest, with *high confidence*, that where violent conflict emerges and persists the capacity to adapt to climate change is reduced for affected populations. This is illustrated in Figure 12-2 which shows that post-conflict societies have low adaptive capacity, where human development acts as a proxy for adaptive capacity (Barnett, 2006; Lind and Eriksen, 2006; Eriksen and Lind, 2009; Adger, 2010).

Armed conflict disrupts markets and destroys infrastructure, limits education and the development of human capital, causes death and injury to workers, and decreases the ability of individuals, communities, and the state to secure credit (Stewart et al., 2001; Goodhand, 2003; Blattman and Miguel, 2010). Conflict thus creates poverty and constrains livelihoods that, in turn, increases vulnerability to the impacts of climate change (Nigel, 2009; Deng, 2010a; Hilson and van Bockstael, 2011). Violent conflict is a major cause of hunger and famines (de Waal, 1993; Messer and Cohen, 2011; Rowhani et al., 2011). Armed conflict interrupts the ability of resource-dependent individuals and communities to access natural resources (Pike, 2004; Detraz, 2009; Kolmannskog, 2010; Raleigh, 2011), and in so doing limits their capacity to adapt to climate change. The denial of strategic space as a tactic in armed conflict (through, e.g., deliberate destruction of crops and spreading of landmines in conflict affected regions) can reduce the capacity of individuals and communities to access natural capital and hence cope with climate variability (Berhe, 2007; Unruh, 2012).

A parallel body of research documents negative feedbacks on adaptive capacity where armed conflict reduces access to ecosystem goods and services, which can lead to inefficient use of natural resources and hence to further environmental degradation. Chronic political instability in Zimbabwe is, for example, implicated in high levels of illegal bush meat hunting (Lindsey et al., 2011). Conflict, and the displacement of large populations, can also alter the abundance and distribution of biodiversity and can result in significant deforestation (Chase and Griffin, 2011; Lindsell et al., 2011; Stevens et al., 2011).

The capacity for collective action is a critical determinant of the capacity to adapt to climate impacts, and this too can be undermined by violent conflict, depending on the nature of violence and the strategies households adopt in response (Deng, 2008, 2010b). When conflict exacerbates existing horizontal inequalities between ethnic or religious groups, foments distrust in local or government institutions, or isolates individuals and households, the social capital that is important for adapting to climate change is also degraded (Bogale and Korf, 2007). Conflict-related displacement also disrupts social networks and makes it difficult to achieve elements of secure livelihoods, such as marriage, access to land, or access to communal social safety nets (Kolmannskog, 2010; Raleigh, 2011). In situations of violent conflict, efforts to address climate change that provide financial or resource flows that can be captured by local elites or illegitimate institutions may compound divisions and exacerbate grievances (Brown et al., 2011; Verhoeven, 2011).

Armed conflict can decrease the capacity of governments to function effectively, which in turn impedes adaptation (Tignino, 2011; Feitelson et al., 2012). For example, research has shown that chronic political conflict has reduced the ability of governance institutions at many scales to effectively manage water resources in the Gaza Strip (Shomar, 2011), parts of the Balkans (Skoulikidis, 2009), and the Middle East (Zeitoun et al., 2012). Instability has affected planning processes around urban land use in Palestine (Raddad et al., 2010) and in regions of Iraq (Hassan, 2010). Armed conflict may also undermine the ability of states to prevent and respond to natural disasters and humanitarian crisis (Keen, 2008). A lack of trust in government commitment or capacity to respond, the presence of police or military forces that lack legitimacy, or recent conflict between government and local forces hampers the ability of these institutions to provide effective relief (Wisner, 2001).

12.5.4. Peace-Building Activities in Promoting Adaptation

In situations where conflict is resources based, it is widely established that resource management has significant potential to contribute to conflict management by channeling competing interests over resources into non-violent resolutions (Conca and Dabelko, 2002; Conca and Wallace, 2009; Lujala and Rustad, 2011; Jensen and Lonergan, 2013). This research on environmental peacebuilding and peacemaking considers that natural resource management, and by extension climate change adaptation, can help build peace to avoid conflicts, and broker peace in conflict situations (Tänzler et al., 2010).

Research on bilateral and multilateral interactions between two or more states from 1948 to 2008 shows strong evidence of significant formal cooperation among river basin riparian states, and no cases of water causing two states to engage in war (Wolf et al., 2003; Wolf, 2007; De Stefano et al., 2010). Transboundary water cooperation, particularly joint management, flood control, and technical cooperation, can form a basis for longer-term cooperation on a range of contentious issues. Efforts at basin-wide institutional development to lower conflict potential focuses on moving from the assertion of conflicting rights to water, to addressing the multiple values of water, and ultimately to sharing benefits across national boundaries (Sadoff and Grey, 2002).

There is an emerging body of evidence about the effectiveness of efforts to enhance cooperation and lower conflict around natural resources (Lujala and Rustad, 2011; Jensen and Lonergan, 2013). Some transboundary conservation areas, referred to as "peace parks," are designed to reduce conflict and enhance cooperation across borders. However, the evidence of the effectiveness of peace parks is limited and ambiguous, with some studies documenting political, economic, and conservation cooperation (Ali and Marton-LaFevre, 2007), while others document conflict generation between local communities, elites, and states (Duffy, 2002).

12.6. State Integrity and Geopolitical Rivalry

Climate change will affect the integrity of states through impacts on critical infrastructure, threats to territorial integrity, and geopolitical rivalry (Gilman et al., 2011). These impacts on infrastructure and geopolitical dimensions directly affect state capacities to provide a range of ecological, economic, social, and political services that fundamentally contribute to human security (Barnett, 2003; Busby, 2008; Barnett et al., 2010; Webersik, 2010).

12.6.1. Critical Infrastructure and State Capacity

Climate change and extreme events are projected to damage a range of critical infrastructure, with water and sanitation, energy, and transportation infrastructure being particularly vulnerable (Rozenzweig et al., 2011; UN-HABITAT, 2011; see also Section 8.2.4). Climate change is expected to exacerbate water supply problems in some urban areas that in turn pose multiple risks to cities. For example, the high-temperature and low-rainfall events that can cause a decline in the supply of water to cool power plants are those that simultaneously increase energy demand for cooling, threatening to disrupt power supply and communications technology. In areas where there may be flooding or increased snow and ice storms, critical infrastructure may be damaged (see Section 8.2.3). Areas that are vulnerable to flooding, landslides, or forest fires will have greater risk of such infrastructure damage (Revi, 2005; Awuor et al., 2008; Adelekan, 2010; Keywood et al., 2013).

Climate change impacts on critical infrastructure will reduce the ability of some states to provide social and public services (see Section 8.2.4.6). For example, power outages stemming from water shortages or storms can in turn lead to reductions in service delivery from hospitals, police forces, and emergency responders. Damage to roads, rails, airports, bridges, and related transport infrastructure can similarly reduce the ability of governments to provide for citizen needs. The impact of thawing permafrost on infrastructure will affect the viability of settlements in high latitudes (Larsen et al., 2008; Dersken et al., 2012; Marino, 2012; see also Sections 28.2.4.2, 28.3.4.3). In countries that are poor or that depend heavily on climate-sensitive activities such as agriculture, climate impacts are expected to lead to significant declines in income and, in turn, government revenues. Mideksa (2010) estimates that climate change impacts will reduce Ethiopia's gross domestic product (GDP) by nearly 10%.

12.6.2. Geopolitical Issues

Analysis of the actions of states and security institutions show that many states view current and anticipated climate changes as contributing to geopolitical concerns (Dabelko, 2009; Smith, 2011). The ability of states to share resources and provide human security is challenged by climate change impacts. Climate change impacts can create contested claims to territory on land and at sea and, in extreme cases, can threaten the territorial integrity or viability of states (Barnett and Campbell, 2010; Houghton et al., 2010; Yamamoto and Esteban, 2010).

For Small Island States and countries with significant areas of soft low-lying coasts (Hanson et al., 2011), sea level rise and extreme events threaten to erode and subsume significant land areas and associated infrastructure and settlements, in the absence of significant adaptation (Nicholls et al., 2011; see also Section 5.4.3.2). For countries made up entirely of low-lying atolls, sea level rise, ocean acidification, and increases in episodes of extreme sea surface temperatures compromise human security for present or future higher populations (Barnett and Campbell, 2010; Fisher, 2011). With projected high levels of sea level rise beyond the end of this century, the physical integrity of low-lying islands is under threat (Barnett and Adger, 2003; Houghton et al., 2010; Section 29.3). The opening of resources, such as the loss of sea ice in

Box 12-6 | Evidence on Security and Geopolitical Dimensions of Climate Change Impacts in the Arctic

Impacts of climate change on the Arctic region exemplify the multiple interactions of human security with geopolitical risks. System-wide changes in the Arctic region affect multiple countries and a global commons resource given Arctic roles in regulating the global climate and ocean systems (Carmack et al., 2012; Duarte et al., 2012). Anticipated changes will contribute to greater geopolitical considerations and human insecurity in the Arctic region. They include food insecurity affecting specific cultures and knowledge systems (outlined in Section 12.3); energy security implications through opening of sub-sea oil and gas reserves; increased shipping; increased pollution; search and rescue challenges; and increased military presence in the region.

The Arctic has been warming at about twice the global rate since 1980, resulting in unprecedented loss in sea ice. The Arctic Ocean is projected to experience major reductions in sea ice, and under some projections would be ice-free by the end of the century (WGI AR5 SPM, *medium confidence*; see also Section 28.1). These changes have implications for land-based infrastructure, shipping, resource extraction, coastal communities, and transport (Holland et al., 2006; Larsen et al., 2008; Stephenson et al., 2011; see also Section 28.3.4). There is *medium evidence* that changes will create or revive terrestrial and maritime boundary disputes among Arctic countries (Borgerson, 2008; Ebinger and Zambetakis, 2009; Lusthaus, 2010). There is little evidence the changing Arctic will become a site for violent conflict between states (Young, 2009; Berkman, 2010; Brosnan et al., 2011). At present, political institutions are providing forums for managing resource competition, new transportation practices, and boundary disputes, but anticipated increased stresses will test these institutions in the future (Ebinger and Zambetakis, 2009).

the Arctic and associated social, economic, and political dimensions (Section 28.2.5), represents an example of climate change impacts being geopolitically significant to states, even in the absence of direct conflict (Box 12-6). Expected sea level rise and resulting coastline changes may affect the location of Exclusive Economic Zones and contribute to conflicts over natural resources or boundary locations (Houghton et al., 2010).

Productive ocean fisheries are already directly affected by climate change, altering the range of important commercial fish stocks (MacNeil et al., 2010). Fishing, as an economic activity, is adapted to highly variable environmental and management conditions; however, the movement of fish stocks (see Section 6.3.2; Berkes et al., 2006) has been suggested to increase transboundary rivalry (MacNeil et al., 2010). For example, northward shifts of mackerel, herring, and capelin stocks are creating economic and geopolitical tension (Sumaila et al., 2011).

The impacts of climate-induced water variability on transboundary water basins constitute a cluster of geopolitical concerns. The high levels of international interdependence on transboundary rivers such as the Nile, Limpopo, Amu Darya, Syr Darya, Mekong, Ganges, Brahmaputra, Tigris, Euphrates, and Indus connect the conditions of the rivers with national development trajectories. Climate change is expected to disrupt the dynamics of runoff (*robust evidence*, *high agreement*; see Section 3.4.5). Warming, for example, will bring forward the snow melt season in all but the coldest regions, altering seasonal water flows (see Section 3.4.5). Such projections have led to concerns over transboundary tensions, particularly where challenges stemming from rising consumption and growing populations are already present (National Research Council, 2012; Swain, 2012).

Research on transboundary conflict and cooperation prioritizes rate of change rather than absolute scarcity in connection with the risk of conflict over water, particularly between states (De Stefano et al., 2012). This focus stems from higher perceived risk of conflict when institutions at local, state, and regional levels have less time to adapt to scarcity or variability by dealing with disputes through diplomatic and other non-violent mechanisms (Wolf et al., 2003; Wolf, 2007; De Stefano et al., 2010, 2012). Sudden changes in flow that heighten risk and challenge institutional responses include declines in seasonal snow or glacial melt. Transboundary basin institutions and international legal mechanisms have demonstrated an ability to manage conflict effectively (Sadoff and Grey, 2002; Wolf, 2007; Brochmann and Hensel, 2009; Dellapenna and Gupta, 2009; Goulden et al., 2009; Dinar et al., 2011; Bernauer and Siegfried, 2012; Feitelson et al., 2012; Gartzke, 2012; Tir and Stinnett, 2012). Other research emphasizes that these transboundary water institutions receive limited financial and political investment, involve unequal or inequitable cooperation between powerful and less powerful countries, and are present in only a limited number of transboundary basins (Conca et al., 2006; Zeitoun and Warner, 2006; Zeitoun and Mirumachi, 2008).

Geoengineering that involves deliberate large-scale manipulation of the environment aimed at reducing negative climate change impacts (Section 20.3) remains an unproven strategy to address climate change. The high levels of uncertainty and high likelihood of differential geographic impacts of geoengineering are anticipated sources of tension or conflict between states (Robock, 2008; Dalby, 2013; Preston, 2013). These include regional effects of solar radiation management on reduced precipitation in specific areas in Asia or in the Sahel (Ricke et al., 2010; Haywood et al., 2013) with negative food production implications. The ability of states to deploy geoengineering unilaterally under limited international legal mechanisms creates the potential for conflict. Examples of security institutions attempting weather modification present the prospect of military involvement in deploying or interdicting geoengineering efforts (Fleming, 2010). The prospect for the securitization of geoengineering responses is contested: geoengineering technologies could be used for hostile purposes but the significance of this possibility is contested (Keith, 2000; Robock, 2008; Corner and Pidgeon, 2010; Brzoska, 2012).

12.7. Synthesis

This chapter shows that climate change and climate variability pose risks to various dimensions of human security, which arise through diverse causal processes and which will be manifest at different scales. There is *high agreement* in the literature for this conclusion that comes from multiple lines of evidence. There are, however, multiple and competing perspectives on the nature and causes of insecurity arising from climate change. For example, farmers in the Sahel are concerned about the risks weather extremes pose to their livelihoods (Mertz et al., 2009), whereas people in Tuvalu report that the cultural impacts of migration are a primary concern rather than climate change directly (Mortreux and Barnett, 2009). Organizations whose mandates include aspects of human security prioritize some risks of climate change over others in line with organizational priorities. For example, the International Organization for Migration is concerned with the implications of climate change for migration, and the U.S. National Intelligence Council is focused on the risk that climate change will increase political instability and geopolitical rivalry. In this respect the framing of climate change as an issue of human security enables conversations across the boundaries of diverse policy communities (Gasper, 2010).

The risks that climate change poses to human security arise through multiple and interacting processes. Those processes also operate across diverse spatial and temporal scales. High levels of complexity mean that no conceptual model or theory captures the full extent of the interactions between all of climate change, livelihoods, culture, migration, and violent conflict. However, as this chapter has shown, there are feedbacks between the key elements of livelihoods, culture, migration, and violent conflict. Figure 12-3 depicts one scenario of interactions between the primary elements discussed in this chapter. Deterioration in livelihoods, influenced in certain cases by climate change and climate variability, is a human security issue in its own right. But such stress to livelihoods also gives rise to migration, which may be unavoidable and undesirable. Such movements, in turn, imply changes in important cultural expressions and practices, and, in the absence of institutions to manage the settlement and integration of migrants in destination areas, can increase the risk of violent conflict. This conflict can in turn undermine livelihoods, impel migration, and weaken valued cultural expressions and practices. The

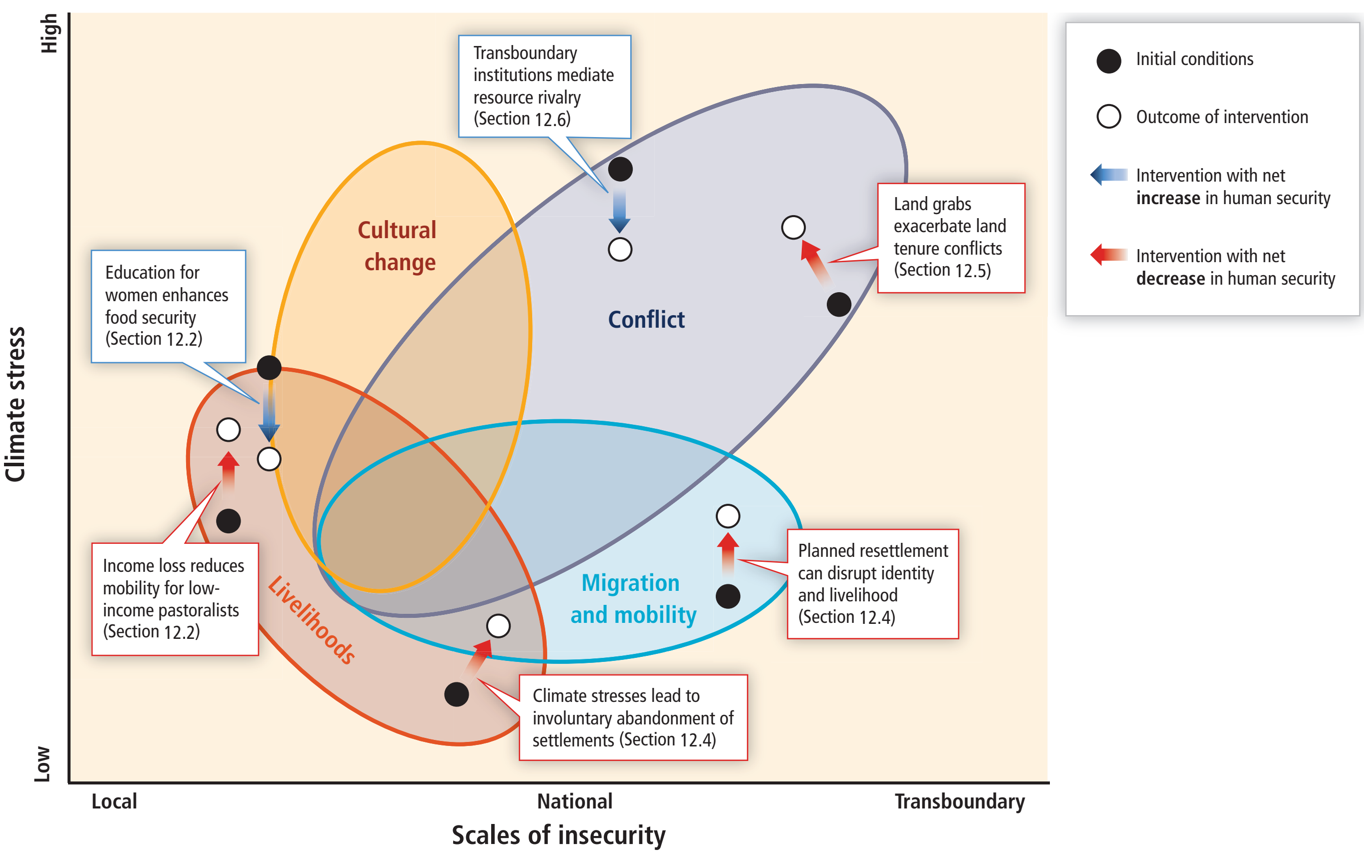
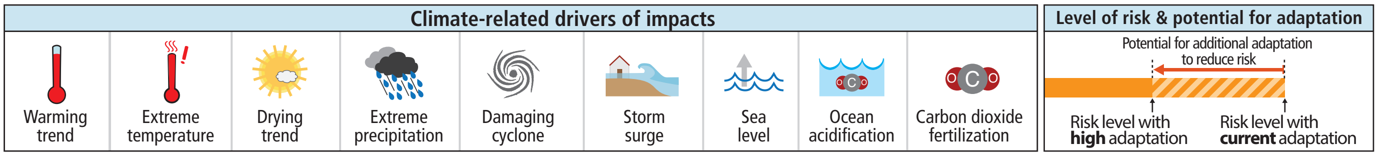


Figure 12-3 | Synthesis of evidence on the impacts of climate change on elements of human security and the interactions between livelihoods, conflict, culture, and migration. Interventions and policies indicated by difference between initial conditions (solid black) and outcome of intervention (white circles). Some interventions (blue arrows) show net increase human security while others (red arrows) lead to net decrease in human security.

Table 12-4 | Examples of important risks from climate change for elements of human security and the potential for risk reduction through mitigation and adaptation. These risks are identified based on this chapter assessment and expert judgments of the authors, with supporting evaluation of evidence and agreement in the relevant chapter sections. Each risk is characterized as *very low*, *low*, *medium*, *high*, or *very high*. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080–2100), for global mean temperature increase of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by symbols. As the assessment considers potential impacts on diverse and incompatible elements and systems, risk levels should not be used to evaluate relative risk between the rows.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation (Very low – Medium – Very high)
Displacement associated with extreme events (*high confidence*) [12.4.1]	Adaptation to extreme events is well understood but poorly implemented even under present climate conditions. Displacement and involuntary migration are often temporary. With increasing climate risks, displacement is more likely to involve permanent migration.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Loss of land, cultural and natural heritage disrupting cultural practices embedded in livelihoods and expressed in narratives, world views, identity, community cohesion, and sense of place (*high confidence*) [12.3.2, 12.3.4]	Cultural values and expressions are dynamic and inherently adaptable and hence adaptation is possible to avoid losses of cultural assets and expressions. Nevertheless cultural integrity will be compromised in these circumstances.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Violent conflict arising from deterioration in resource dependent livelihoods such as agriculture and pastoralism (*high confidence*) [12.5.1]	Adaptation options: Buffering rural incomes against climate shocks, e.g., through livelihood diversification, income transfers, and social safety net provision; Early warning mechanisms to promote effective risk reduction; Well-established strategies for managing violent conflict that are effective but require significant resources, investment, and political will.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Geopolitical competition over access to Arctic resources that escalates into dangerous tensions and crises (*high confidence*) [12.6.2]	There are international organizations and elements of international law that regulate competition and access and provide mechanisms for resolving disputes. There are strong transnational networks that are relevant for joint problem solving. Hence adaptation action has significant potential to reduce risks associated with geopolitical rivalry.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
New or exacerbated conflict through land acquisition for climate change mitigation and adaptation (*medium confidence*) [12.5.2]	Climate change mitigation (e.g., expansion of biofuel production area) and adaptation action (e.g., set-back of coastal land) can exacerbate conflicts when they are already manifest around land and water availability and scarcity. The extent of insecurity and instability from such mitigation and adaptation activities depends on the displacement of populations and the inclusiveness of the planning processes. Careful planning processes can therefore be used to ameliorate the risk of conflict	*Cumulative climate risks act as incentives for mitigation and adaptation action*	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

evidence in this chapter shows that some interventions and policies enhance human security, while others inadvertently can exacerbate insecurity (depicted in red and blue arrows in Figure 12-3).

Each dimension of human security examined in this chapter demonstrates the potential for adaptation to minimize risks to human security. Again there is *high agreement* on this finding, reflected in Table 12-4, with multiple lines of evidence from food security, to migration, to conflict resolution. This chapter suggests that often institutions anticipate and react to these risks to human security (Ribot, 2011; Artur and Hilhorst, 2012). These institutional responses can significantly dampen or amplify the way changes in climate change and extreme events give rise to human insecurity. Table 12-4 summarizes a number of example risks to human security, with the final column demonstrating that these risks can be ameliorated through adaptation for many of those examples. In general, higher levels of climate change impacts become less amenable to adaptation.

Adaptation and mitigation strategies and interventions can also affect human insecurity in positive and negative directions. There is evidence that adaptation and mitigation strategies that are imposed on communities are more likely to impact negatively on human security than those that are consistent with their capabilities and values (*limited evidence*, *medium agreement*; Ensor and Berger, 2009; Barnett and O'Neill, 2012;

Marino, 2012; Mercer et al., 2012). Adaptation strategies that seek to reduce exposure to climate change, through the development of large infrastructure or the resettlement of communities against their will, carry risks of disrupted livelihoods, displaced populations, deterioration of valued cultural expressions and practices, and in some cases violent conflict (Table 12-4). Similarly, mitigation policies that entail changes in property regimes that are not consistent with resource ownership and use can impact negatively on human security. There is strong evidence to demonstrate that mitigation activities that align with local interests and institutions can have significant co-benefits for human security, especially through human health (Klein et al., 2005; Ayers and Huq, 2009; Laukkonen et al., 2009; Haines et al., 2009; Moser 2012; West et al., 2013).

In summary, climate change is one of many risks to the vital core of material well-being and culturally specific elements of human security that vary depending on location and circumstance. While there is much uncertainty about the future impacts of climate change on human security, on the basis of current evidence about the observed impacts of climate change on environmental conditions, climate change will be an increasingly important driver of human insecurity in the future (see Figure 12-3). Location and circumstance specific factors include poverty, discrimination, and inadequate provision of public services and public health, and opportunities for education. Investments in institutional responses to facilitate adaptation can dampen many of the potential adverse effects of climate change on human security (see Figure 12-3). Conversely, inappropriate climate policy responses may accelerate and amplify human insecurity including conflict.

At very high levels of projected warming, all aspects of human security discussed in this chapter will be adversely affected (e.g., in high-latitude regions: Box 12-6). At high levels of warming, the rate of changes in environmental conditions in most places will be without any precedent in human history (New et al., 2011). Hence analysis concerning human security in those circumstances of very high impacts (as depicted in Table 12-4) is uncertain. Much of the current literature on human security and climate change is informed by contemporary relationships and observation and hence is limited in analyzing the human security implications of rapid or severe climate change.

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13 Livelihoods and Poverty

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Executive Summary

This chapter discusses how livelihoods, poverty and the lives of poor people, and inequality interact with climate change, climate variability, and extreme events in multifaceted and cross-scalar ways. It examines how current impacts of climate change, projected impacts up until 2100, and responses to climate change affect livelihoods and poverty. The Fourth Assessment Report stated that socially and economically disadvantaged and marginalized people are disproportionally affected by climate change. However, no comprehensive review of climate change, poverty, and livelihoods has been undertaken to date by the IPCC. This chapter addresses this gap, presenting evidence of the dynamic interactions between these three principal factors. At the same time, the chapter recognizes that climate change is rarely the only factor that affects livelihood trajectories and poverty dynamics; climate change interacts with a multitude of non-climatic factors, which makes detection and attribution challenging.

Climate-related hazards exacerbate other stressors, often with negative outcomes for livelihoods, especially for people living in poverty (*high confidence*).

- Climate-related hazards, including subtle shifts and trends to extreme events, affect poor people's lives directly through impacts on livelihoods, such as losses in crop yields, destroyed homes, food insecurity, and loss of sense of place, and indirectly through increased food prices (*robust evidence*, *high agreement*). {13.2.1, 13.3}
- Changing climate trends lead to shifts in rural livelihoods with mixed outcomes, such as from crop-based to hybrid livestock-based livelihoods or to wage labor in urban employment. Climate change is one stressor that shapes dynamic and differential livelihood trajectories (*robust evidence*, *high agreement*). {13.1.4, 13.2.1.2}
- Urban and rural transient poor who face multiple deprivations slide into chronic poverty as a result of extreme events, or a series of events, when unable to rebuild their eroded assets. Poverty traps also arise from food price increase, restricted mobility, and discrimination (*limited evidence*, *high agreement*). {13.2.1.3-4}
- Many events that affect poor people are weather-related and remain unrecognized by standard climate observations in many low-income countries, owing to short time series and geographically sparse, aggregated, or partial data, inhibiting detection and attribution. Such events include short periods of extreme temperature, minor changes in the distribution of rainfall, and strong wind events (*robust evidence*, *high agreement*). {13.2.1}

Observed evidence suggests that climate change and climate variability worsen existing poverty, exacerbate inequalities, and trigger both new vulnerabilities and some opportunities for individuals and communities. Poor people are poor for different reasons and thus are not all equally affected, and not all vulnerable people are poor. Climate change interacts with non-climatic stressors and entrenched structural inequalities to shape vulnerabilities (*very high confidence*, based on *robust evidence*, *high agreement*).

- Socially and geographically disadvantaged people exposed to persistent inequalities at the intersection of various dimensions of discrimination based on gender, age, race, class, caste, indigeneity, and (dis)ability are particularly negatively affected by climate change and climate-related hazards. Context-specific conditions of marginalization shape multidimensional vulnerability and differential impacts. {13.1.2.3, 13.1.3., 13.2.1.5}
- Existing gender inequalities are increased or heightened by climate-related hazards. Gendered impacts result from customary and new roles in society, often entailing higher workloads, occupational hazards indoors and outdoors, psychological and emotional distress, and mortality in climate-related disasters. {13.2.1.5}
- There is little evidence that shows positive impacts of climate change on poor people, except isolated cases of social asset accumulation, agricultural diversification, disaster preparedness, and collective action. The more affluent often take advantage of shocks and crises, given their flexible assets and power status. {13.1.4, 13.2.1.4; Figure 13-3}

Climate change will create new poor between now and 2100, in developing and developed countries, and jeopardize sustainable development. The majority of severe impacts are projected for urban areas and some rural regions in sub-Saharan Africa and Southeast Asia (*medium confidence*, based on *medium evidence*, *medium agreement*).

- Future impacts of climate change, extending from the near term to the long term, mostly expecting 2°C scenarios, will slow down economic growth and poverty reduction, further erode food security, and trigger new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger. {13.2.2.2, 13.2.2.4, 13.4}

- Climate change will exacerbate multidimensional poverty in most developing countries, including high mountain states, countries at risk from sea level rise, and countries with indigenous peoples. Climate change will also create new poverty pockets in countries with increasing inequality, in both developed and developing countries. {13.2.2}
- Wage-labor dependent poor households that are net buyers of food will be particularly affected due to food price increases, in urban and rural areas, especially in regions with high food insecurity and high inequality (particularly in Africa), although the agricultural self-employed could benefit {13.2.2.3-4}

Current policy responses for climate change mitigation or adaptation will result in mixed, and in some cases even detrimental, outcomes for poor and marginalized people, despite numerous potential synergies between climate policies and poverty reduction (*medium confidence*, based on *limited evidence*, *high agreement*).

- Mitigation policies with social co-benefits expected in their design, such as Clean Development Mechanism (CDM) and Reduction of Emissions from Deforestation and Forest Degradation (REDD+), have had limited or no effect in terms of poverty alleviation and sustainable development. {13.3.1.1-2}
- Mitigation efforts focused on land acquisition for biofuel production show preliminary negative impacts on the lives of poor people, such as dispossession of farmland and forests, in many developing countries, particularly for indigenous peoples and (women) smallholders. {13.3.1.4}
- Insurance schemes, social protection programs, and disaster risk reduction may enhance long-term livelihood resilience among poor and marginalized people, if policies address multidimensional poverty. {13.3.2.2, 13.4.1}
- Climate-resilient development pathways will have only marginal effects on poverty reduction, unless structural inequalities are addressed and needs for equity among poor and non-poor people are met. {13.4.2}

13.1. Scope, Delineations, and Definitions: Livelihoods, Poverty, and Inequality

Understanding the impacts of climate change on livelihoods and poverty requires examining the complexities of poverty and the lives of poor and non-poor people, as well as the multifaceted and cross-scalar intersections of poverty and livelihoods with climate change. This chapter is devoted to exploring poverty in relation to climate change, a novelty in the IPCC. It uses a livelihood lens to assess the interactions between climate change and multiple dimensions of poverty. We use the term "the poor," not to homogenize, but to describe people living in poverty, people facing multiple deprivations, and the socially and economically disadvantaged, as part of a conceptualization broader than income-based measures of poverty, acknowledging gradients of prosperity and poverty. This livelihood lens also reveals how inequalities perpetuate poverty to shape differential vulnerabilities and in turn the differentiated impacts of climate change on individuals and societies. The chapter first presents the concepts of livelihoods, poverty, and inequality, and their relationships to each other and to climate change. Second, it describes observed impacts of weather events and climate on livelihoods and rural and urban poor people as well as projected impacts up to 2100. We use "weather events and climate" as an umbrella term for climate change, climate variability, and extreme events, and also highlight subtle shifts in precipitation and localized weather events. Third, this chapter discusses impacts of climate change mitigation and adaptation responses on livelihoods and poverty. Finally, it outlines implications for poverty alleviation efforts and climate-resilient development pathways.

Livelihoods and Poverty is a new chapter in the AR5. Although the WGII AR4 contributions mentioned poverty, as one of several non-climatic factors contributing to vulnerability, as a serious obstacle to effective adaptation, and in the context of endemic poverty in Africa (Chapters 7, 8, 18, 20), no systematic assessment was undertaken. Livelihoods were more frequently addressed in the AR4 and in the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX), predominantly with reference to livelihood strategies and opportunities, diversification, resource-dependent communities, and sustainability. Yet, a comprehensive livelihood lens for assessing impacts was lacking. This chapter addresses these gaps. It assesses how climate change intersects with other stressors to shape livelihood choices and trajectories, to affect the spatial and temporal dimensions of poverty dynamics, and to reduce or exacerbate inequalities given differential vulnerabilities.

13.1.1. Livelihoods

Livelihoods (see also Glossary) are understood as the ensemble or opportunity set of capabilities, assets, and activities that are required to make a living (Chambers and Conway, 1992; Ellis et al., 2003). They depend on access to natural, human, physical, financial, social, and cultural capital (assets); the social relations people draw on to combine, transform, and expand their assets; and the ways people deploy and enhance their capabilities to act and make lives meaningful (Scoones, 1998; Bebbington, 1999). Livelihoods are dynamic and people adapt and change their livelihoods with internal and external stressors. Ultimately, successful livelihoods transform assets into income, dignity, and agency, to improve living conditions, a prerequisite for poverty alleviation (Sen, 1981).

Livelihoods are universal. Poor and rich people both pursue livelihoods to make a living. However, as shown in this chapter, the adverse impacts of weather events and climate increasingly threaten and erode basic needs, capabilities, and rights, particularly among poor and disenfranchised people, in turn reshaping their livelihoods (UNDP, 2007; Leary et al., 2008; Adger, 2010; Quinn et al., 2011). Some livelihoods are directly climate sensitive, such as rainfed smallholder agriculture, seasonal employment in agriculture (e.g., tea, coffee, sugar), fishing, pastoralism, and tourism. Climate change also affects households dependent on informal livelihoods or wage labor in poor urban settlements, directly through unsafe settlement structures or indirectly through rises in food prices or migration.

13.1.1.1. Dynamic Livelihoods and Trajectories

A livelihood lens is a grounded and multidimensional perspective that recognizes the flexibility and constraints with which people construct their complex lives and adapt their livelihoods in dynamic ways. By paying attention to the wider institutional, cultural, and policy contexts as well as shocks, seasonality, and trends, this lens reveals processes that push people onto undesirable trajectories or toward enhanced well-being. Better infrastructure and technology as well as diversification of assets, activities, and social support capabilities can boost livelihoods, spreading risks and broadening opportunities (Batterbury, 2001; Ellis et al., 2003; Clot and Carter, 2009; Carr, 2013; Reed et al., 2013). The sustainable livelihoods framework (Chambers and Conway, 1992) is widely used for identifying how specific strategies may lead to cycles of livelihood improvements or critical thresholds beyond which certain livelihoods are no longer sustainable (Sabates-Wheeler et al., 2008). It emerged as a reaction to the predominantly structural views of poverty and "underdevelopment" in the 1970s and became adopted by many researchers and development agencies (Ellis and Biggs, 2001). With the neoliberal turn in the late 1980s, the livelihoods approach became associated with a more individualistic development agenda, stressing various forms of capital (Scoones, 2009). Consequently, it has been criticized for its analytical limitations, such as measuring capitals or assets, especially social capital, and for not sufficiently explaining wider structural processes (e.g., policies) and ecological impacts of livelihood decisions (Small, 2007; Scoones, 2009). An overemphasis on capitals also eclipses power dynamics and the position of households in class, race, and other dimensions of inequality (Van Dijk, 2011).

13.1.1.2. Multiple Stressors

Livelihoods rarely face only one stressor or shock at a time. The literature emphasizes the synergistic relationship between weather events and climate and a variety of other environmental, social, economic, and political stressors; together, they impinge on livelihoods and reinforce each other in the process, often negatively (Reid and Vogel, 2006; Schipper and Pelling, 2006; Easterling et al., 2007; IPCC, 2007; Morton, 2007; Tschakert, 2007; O'Brien et al., 2008; Eriksen and Silva, 2009; Eakin and Wehbe, 2009; Ziervogel et al., 2010). "Double losers" may

Frequently Asked Questions

FAQ 13.1 | What are multiple stressors and how do they intersect with inequalities to influence livelihood trajectories?

Multiple stressors are simultaneous or subsequent conditions or events that provoke/require changes in livelihoods. Stressors include climatic (e.g., shifts in seasons), socioeconomic (e.g., market volatility), and environmental (e.g., destruction of forest) factors, that interact and reinforce each other across space and time to affect livelihood opportunities and decision making (see Figure 13-1). Stressors that originate at the macro level include climate change, globalization, and technological change. At the regional, national, and local levels, institutional context and policies shape possibilities and pitfalls for lessening the effects of these stressors. Which specific stressors ultimately result in shocks for particular livelihoods and households is often mediated by institutions that connect the local level to higher levels. Moreover, inequalities in low-, medium-, and high-income countries often amplify the effects of these stressors. This is particularly the case for livelihoods and households that have limited asset flexibility and/or those that experience disadvantages and marginalization due to gender, age, class, race, (dis)ability, or being part of a particular indigenous or ethnic group. Weather events and climate compound these stressors, allowing some to benefit and enhance their well-being while others experience severe shocks and may slide into chronic poverty. Who is affected, how, where, and for how long depends on local contexts. For example, in the Humla district in Nepal, gender roles and caste relations influence livelihood trajectories in the face of multiple stressors including shifts in the monsoon season (climatic), limited road linkages (socioeconomic), and high elevation (environmental). Women from low castes have adapted their livelihoods by seeking more day-labor employment, whereas men from low castes ventured into trading on the Nepal-China border, previously an exclusively upper caste livelihood.

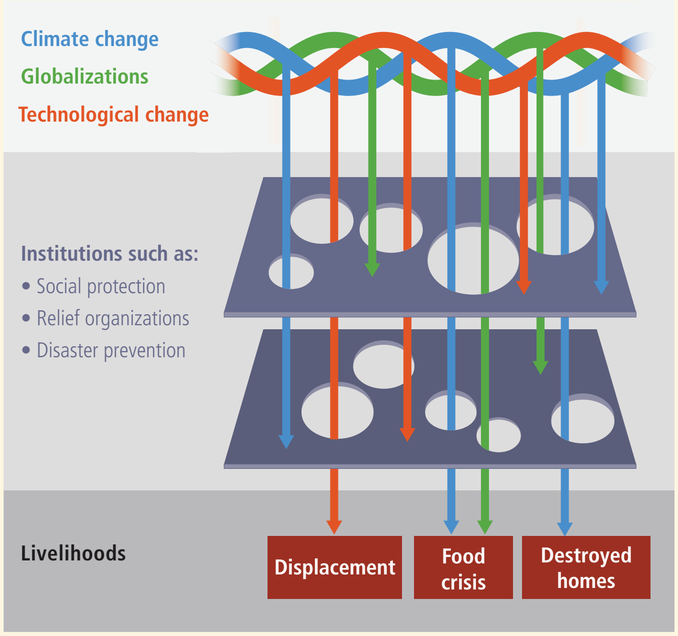


Figure 13-1 | Multiple stressors related to climate change, globalizations, and technological change interact with national and regional institutions to create shocks to place-based livelihoods, inspired by Reason (2000).

emerge from simultaneous exposure to climatic change and other stressors such as the spread of infectious diseases, rapid urbanization, and economic globalization, where climate change acts as a threat multiplier, further marginalizing vulnerable groups (O'Brien and Leichenko, 2000; Eriksen and Silva, 2009). Climatic and other stressors affect livelihoods at different scales: spatial (e.g., village, nation) or temporal (e.g., annual, multi-annual). Both direct and indirect impacts are often amplified or weakened at different levels. Global or regional processes generate a variety of stressors, typically mediated by cross-level institutions, that result in locally experienced shocks (Reid and Vogel, 2006; Thomas et al., 2007; Paavola, 2008; Pouliotte et al., 2009; see also Figure 13-1 in FAQ 13.1).

Multiple stressors, simultaneous and in sequence, shape livelihood dynamics in distinct ways due to inequalities and differential vulnerabilities between and within households. More affluent households may be able to capitalize on shocks and crises while poorer households with fewer options are forced to erode their assets. Limited ability to adapt and some coping strategies may result in adverse consequences. Such maladaptive actions (see Glossary, and Chapters 14, 16) undermine the long-term sustainability of livelihoods, resulting in downward trajectories, poverty traps, and exacerbated inequalities (Ziervogel et al., 2006; Tanner and Mitchell, 2008; Barnett and O'Neill, 2010).

13.1.2. Dimensions of Poverty

Poverty is a complex concept with conflicting definitions and considerable disagreement in terms of framings, methodologies, and measurements. Despite different approaches emphasizing distinct aspects of poverty at the individual or collective level—such as income, capabilities, and quality of life (Laderchi et al., 2003)—poverty is recognized as multidimensional (UNDP, 1990). It is influenced by social, economic, institutional, political, and cultural drivers; its reversal requires efforts in multiple domains that promote opportunities and empowerment, and enhance security (World Bank, 2001). In addition to material deprivation, multidimensional conceptions of poverty consider a sense of belonging and socio-cultural heritage (O'Brien and Leichenko, 2003), identity, and agency, or "the culturally constrained capacity to act" (Ahearn, 2001, p. 54). The AR4 identified poverty as "the most serious obstacle to effective adaptation" (Confalonieri et al., 2007, p. 417).

13.1.2.1. Framing and Measuring Multidimensional Poverty

Over the last 6 decades, conceptualizations of poverty have broadened, expanding the basis for understanding poverty and its drivers. Poverty measurements now better capture multidimensional characteristics and spatial and temporal nuances. Attention to multidimensional deprivations—such as hunger; illiteracy; unclean drinking water; lack of access to health, credit, or legal services; social exclusion; and disempowerment—have shifted the analytical lens to the dynamics of poverty and its institutionalization within social and political norms (UNDP, 1994; Sen, 1999; World Bank, 2001). Regardless of these shifting conceptualizations over time, comparable and reliable measures remain challenging and income per capita remains the default method to account for the depth of global poverty.

In climate change literature, poverty and poverty reduction have been predominantly defined through an economic lens, reflecting various growth and development discourses (Sachs, 2006; Collier, 2007). Less attention has been paid to relational poverty, produced through material social relations and in relation to privilege and wealth (Sen, 1976; Mosse, 2010; Alkire and Foster, 2011; UNDP, 2011a). Yet, such framing allows for addressing the social and political contexts that generate and perpetuate poverty and structural vulnerability to climate change (McCright and Dunlap, 2000; Bandiera et al., 2005; Leichenko and O'Brien, 2008). Many climate policies to date favor market-based responses using sector-specific and economic growth models of development, although some responses may slow down achievements of international development such as those outlined in the Millennium Development Goals (MDGs). For instance, the World Bank encourages "mitigation, adaptation, and the deployment of technologies" that "allow[s] developing countries to continue their growth and reduce poverty" (World Bank, 2010, p. 257), mainly promoted through market tools. A relational approach to poverty highlights the integral role of poor people in all social relations (Pogge, 2009; O'Brien et al., 2010; UNRISD, 2010; Gasper et al., 2013; St.Clair and Lawson, 2013). It emphasizes equity, human security, and dignity (O'Connor, 2002; Mosse, 2010). Akin to the capabilities approach (Sen, 1985, 1999; Nussbaum, 2001, 2011; Alkire, 2005), the relational approach stresses the needs, skills, and aims of poor people while tackling structural causes of poverty, inequalities, and uneven power relations.

The IPCC AR4 (Yohe et al., 2007) highlighted that—with *very high confidence*—climate change will impede the ability of nations to alleviate poverty and achieve sustainable development, as measured by progress toward the MDGs. Empirical assessments of the impact of

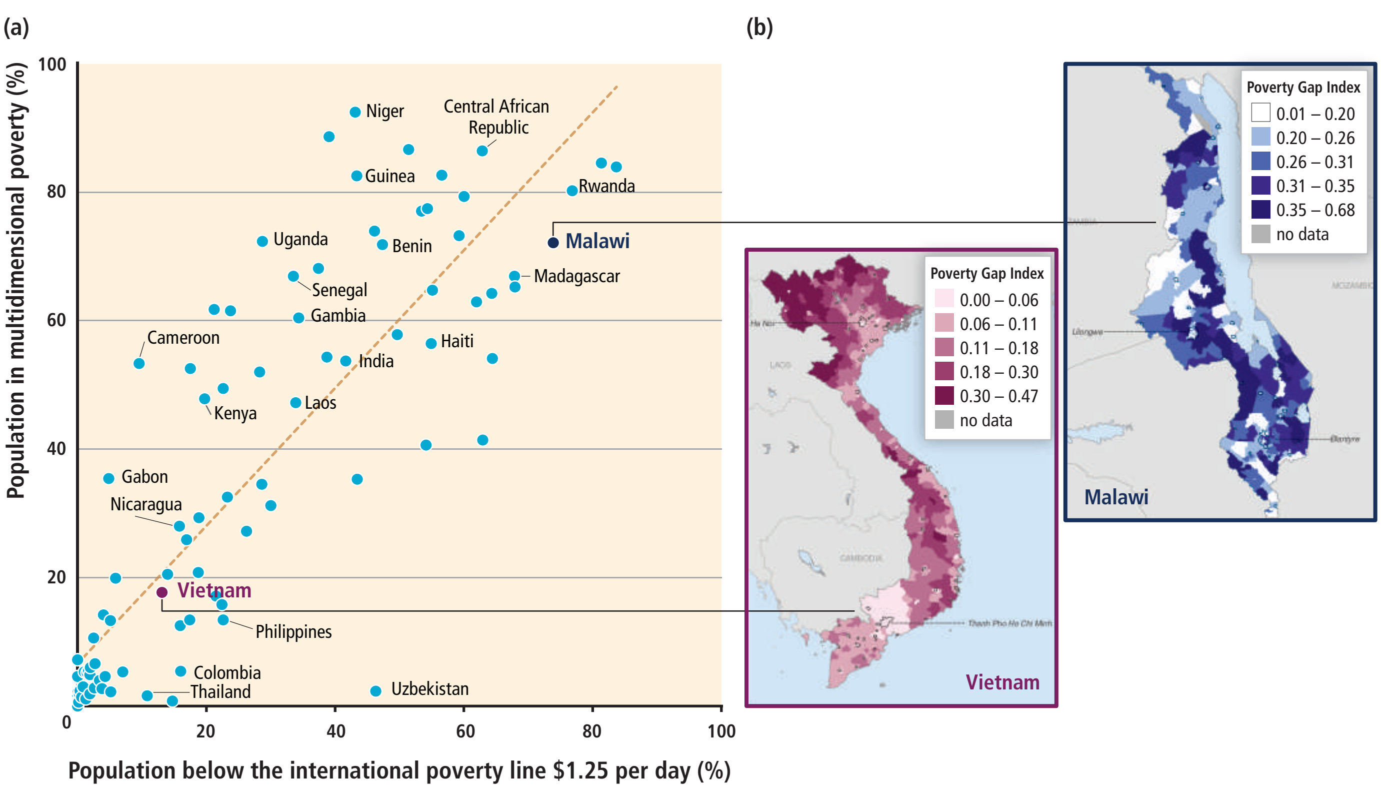


Figure 13-2 | (a) Multidimensional poverty and income-based poverty using the International Poverty Line $1.25 per day (in Purchasing Power Parity terms), with linear regression relationship (dotted line) based on 96 countries (UNDP, 2011b). The position of the countries relative to the dotted line illustrates the extent to which these two poverty measures are similar or divergent. (b) The map insets show the intensity of poverty in two countries, based on the Poverty Gap Index at district level (per capita measure of the shortfall in welfare of the poor from the poverty line, expressed as a ratio of the poverty line): the darker the shading, the larger the shortfall.

climate change on MDG attainment are limited (Fankhauser and Schmidt-Traub, 2011), and the failure to reach these goals by 2015 has significant non-climatic causes (e.g., Hellmuth et al., 2007; UNDP, 2007). The 2010 UNDP Multidimensional Poverty Index, measuring intensity of poverty based on patterns of simultaneous deprivations in basic services (education, health, and standard of living) and core human functionings, states that close to 1.7 billion people face multidimensional poverty, a significantly higher number than the 1.2 billion (World Bank, 2012a) indicated by the International Poverty Line (IPL) set at $1.25 per day. Figure 13-2 depicts country-level examples of how the two poverty measures differ.

Caution is required for poverty projections. Estimates of poverty made using national accounts means (see Chapter 19) yield drastically different estimates to those produced by survey means, both for current estimates and future projections (Edward and Sumner, 2013a). Diverse conceptions of poverty further complicate projections, as multidimensional conceptions rely on concepts difficult to measure and compare. Data availability constrains current estimates let alone projections and their core assumptions (Alkire and Santos, 2010; Karver et al., 2012).

13.1.2.2. Geographic Distribution and Trends of the World's Poor

Geographic patterns of poverty are uneven and shifting. Despite its limitations, most comparisons to date rely on the IPL. In the remainder of the text, we use the World Bank income-based poverty categories for countries (low-income countries, lower-middle-income countries, upper-middle-income countries, and high-income countries); these categories are more precise and more accurate for describing climate change impacts on poverty than the terminology adopted in the Summary for Policymakers and the respective chapter Executive Summaries (i.e., 'developing' and 'developed' countries). Moreover, much of the assessed literature is based on these categories. In 1990, most of the world's $1.25 and $2 poor lived in low-income countries (LICs). By 2008, the majority of the poor living on $1.25 and $2 (>70%) resided in lower- and upper-middle-income countries (LMICs and UMICs), in part because some populous LICs such as India, Nigeria, and Pakistan grew in per capita income to MIC status (Sumner, 2010, 2012a). Estimates suggest about 1 billion people currently living on less than $1.25 per day in MICs and a second billion between $1.25 and $2, with an additional 320 million and 170 million in LICs, respectively (Sumner, 2012b). About 70% of the poor subsisting on $1.25 per day live in rural areas in the global South (IFAD, 2011), despite worldwide urbanization. Yet, this poverty line understates urban poverty as it does not fully account for the higher costs of food and non-food items in many urban contexts (Mitlin and Satterthwaite, 2013). Of the approximately 2.4 billion living on less than $2 per day, half live in India and China. At the same time, relative poverty is rising in HICs. Many European countries face rapid increases in poverty, unemployment, and the number of working poor due to recent austerity measures. For example, 20% of Spanish citizens were ranked poor in 2009 (Ortiz and Cummins, 2013). See also Chapter 23.

The shift in distribution of global poverty toward MICs and the increase in relative poverty in HICs challenge the orthodox view that most of the world's poorest people live in the poorest countries, and suggests that substantial pockets of poverty persist in countries with higher levels of average per capita income. Understanding this shift in the geography of poverty and available social safety nets is vital for assessing climate change impacts on poverty. To date, both climate finance and research on climate impacts and vulnerabilities are directed largely toward LICs. Less attention has been paid to poor people in MICs and HICs. In the upper and lower MICs, the incidence of $2 per day poverty, despite declines, remains as high as 60% and 20%, respectively (Sumner, 2012b).

Projections for 2030 suggest $2 per day poverty as high as 963 million people in sub-Saharan Africa and 851 million in India (Sumner et al., 2012; Edward and Sumner, 2013a). However, uncertainty is high in terms of future growth and inequality trends; by 2030, $1.25 and $2 per day global poverty could be reduced to 300 million and 600 million respectively or remain at or above current levels, including in stable MICs (Edward and Sumner, 2013a). These future scenarios become more uncertain if climate change impacts on people who are socially and economically disadvantaged are taken into account or diversion of resources from poverty reduction and social protection to mitigation strategies is considered.

13.1.2.3. Spatial and Temporal Scales of Poverty

Poverty is also socially distributed, across spatial and temporal scales. Not everybody is poor in the same way. Spatially, factors such as access to and control over resources and institutional linkages from individuals to the international level affect poverty distribution (Anderson and Broch-Due, 2000; Murray, 2002; O'Laughlin, 2002; Rodima-Taylor, 2011). Even at the household level, poverty differs between men and women and age groups, yet data constraints impede systematic intra-household analysis (Alkire and Santos, 2010). The distribution of poverty also varies temporally, typically between chronic and transient poverty (Sen, 1981, 1999). Chronic poverty describes an individual deprivation, per capita income, or consumption levels below the poverty line over many years (Gaiha and Deolalikar, 1993; Jalan and Ravallion, 2000; Hulme and Shepherd, 2003). Transient poverty denotes a temporary state of deprivation, and is frequently seasonal and triggered by an individual's or household's inability to maintain income or consumption levels in times of shocks or crises (Jalan and Ravallion, 1998).

Individuals and households can fluctuate between different degrees of poverty and shift in and out of deprivation, vulnerability, and well-being (Leach et al., 1999; Little et al., 2008; Sallu et al., 2010). Yet, the most disadvantaged often find themselves in poverty traps, or situations in which escaping poverty becomes impossible without external assistance due to unproductive or inflexible asset portfolios (Barrett and McPeak, 2006). A poverty trap can also be seen as a "critical minimum asset threshold, below which families are unable to successfully educate their children, build up their productive assets, and move ahead economically over time" (Carter et al., 2007 p. 837). As of 2008, a total of 320 to 443 million of people were trapped in chronic poverty (Chronic Poverty Research Centre, 2008), leading Sachs (2006) to label less than $1.25 per day poverty as a trap in itself. Poverty traps at the national level are often related to poor governance, reduced foreign investment, and conflict (see Chapters 10, 12).

13.1.3. Inequality and Marginalization

Specific livelihoods and poverty alone do not necessarily make people vulnerable to weather events and climate. The socially and economically disadvantaged and the marginalized are disproportionately affected by the impacts of climate change and extreme events (*robust evidence*; Kates, 2000; Paavola and Adger, 2006; Adger et al., 2007; Cordona et al., 2012). The AR4 identified poor and indigenous peoples in North America (Field et al., 2007) and in Africa (Boko et al., 2007) as highly vulnerable. Vulnerability, or the propensity or predisposition to be adversely affected (IPCC, 2012a) by climatic risks and other stressors (see also Glossary), emerges from the intersection of different inequalities, and uneven power structures, and hence is socially differentiated (Sen, 1999; Banik, 2009; IPCC, 2012a). Vulnerability is often high among indigenous peoples, women, children, the elderly, and disabled people who experience multiple deprivations that inhibit them from managing daily risks and shocks (Eriksen and O'Brien, 2007; Ayers and Huq, 2009; Boyd and Juhola, 2009; Barnett and O'Neill, 2010; O'Brien et al., 2010; Petheram et al., 2010) and may present significant barriers to adaptation.

Global income inequality has been relatively consistent since the late 1980s. In 2007, the top quintile of the world's population received 83% of the total income whereas the bottom quintile took in 1% (Ortiz and Cummins, 2011). Since 2005, between-country inequality has been falling more quickly and, consequently, has triggered a notable decline in total global inequality in the last few years (Edward and Sumner, 2013b). However, within-country inequality is rising in Asia, especially China, albeit from relatively low levels, and is falling in Latin America, albeit from very high levels, while trends in sub-Saharan Africa are difficult to discern regionally (Ravallion and Chen, 2012). Income inequality is rising in many fast growing LICs and MICs (Dollar et al., 2013; Edward and Sumner, 2013b). It is also growing in many HICs owing to a combination of factors such as changing tax systems, privatization of social services, labor market regulations, and technological change (OECD, 2011). The 2008 financial crisis, combined with climate change, has further threatened economic growth in HICs, such as the UK, and resources available for social policies and welfare systems (Gough, 2010). Recognizing how inequality and marginalization perpetuate poverty is a prerequisite for climate-resilient development pathways (see Section 13.4; Chapters 1, 20, 27).

13.1.4. Interactions between Livelihoods, Poverty, Inequality, and Climate Change

This chapter opens its analytical lens from a conventional focus on the poor in LICs as the prime victims of climate change to a broader understanding of livelihood and poverty dynamics and inequalities, revealing the highly unequal impacts of climate change. It highlights the complex relationship between climate change and poverty. The SREX recognizes that addressing structural inequalities that create and sustain poverty and vulnerability (Huq et al., 2005; Schipper, 2007; Lemos et al., 2007; Boyd and Juhola, 2009; Williams, 2010; Perch, 2011) is a crucial precondition for confronting climate change (IPCC, 2012a). If ignored, uneven social relations that disproportionally burden poor people with climate change's negative impacts provoke maladaptation (Barnett and O'Neill, 2010).

Poverty and persistent inequality are the "most salient of the conditions that shape climate-related vulnerability" (Ribot, 2010, p. 50). They affect livelihood options and trajectories, and create conditions in which people have few assets to liquidate in times of hardship or crisis (Mearns and Norton, 2010). People who are poor and marginalized usually have the least buffer to face even modest climate hazards and suffer most from successive events with little time for recovery. They are the first to experience asset erosion, poverty traps, and barriers and limits to adaptation. As shown in Sections 13.2 and 13.3, climate change is an additional burden to people in poverty (*very high confidence*), and it

Frequently Asked Questions

FAQ 13.2 | How important are climate change-driven impacts on poverty compared to other drivers of poverty?

Climate change-driven impacts are one of many important causes of poverty. They often act as a threat multiplier, meaning that the impacts of climate change compound other drivers of poverty. Poverty is a complex social and political problem, intertwined with processes of socioeconomic, cultural, institutional, and political marginalization, inequality, and deprivation, in low-, middle-, and even high-income countries. Climate change intersects with many causes and aspects of poverty to worsen not only income poverty but also undermine well-being, agency, and a sense of belonging. This complexity makes detecting and measuring attribution to climate change exceedingly difficult. Even modest changes in seasonality of rainfall, temperature, and wind patterns can push transient poor and marginalized people into chronic poverty as they lack access to credit, climate forecasts, insurance, government support, and effective response options, such as diversifying their assets. Such shifts have been observed among climate-sensitive livelihoods in high mountain environments, drylands, and the Arctic, and in informal settlements and urban slums. Extreme events, such as floods, droughts, and heat waves, especially when occurring in a series, can significantly erode poor people's assets and further undermine their livelihoods in terms of labor productivity, housing, infrastructure, and social networks. Indirect impacts, such as increases in food prices due to climate-related disasters and/or policies, can also harm both rural and urban poor people who are net buyers of food.

will force poor people from transient into chronic poverty and create new poor (*medium confidence*).

The complex interactions among weather events and climate, dynamic livelihoods, multidimensional poverty and deprivation, and persistent inequalities, including gender inequalities, create an ever-shifting context of risk. The SREX concluded that climate change, climate variability, and extreme events synergistically add on to and often reinforce other environmental, social, and political calamities (IPCC, 2012a). Despite the recognition of these complex interactions, the literature shows no single conceptual framework that captures them concurrently, and few studies exist that overlay gradual climatic shifts or rapid-onset events onto livelihood risks. Hence, explicit attention to how livelihood dynamics interact with climatic and non-climatic stressors is useful for identifying processes that push poor and vulnerable people onto undesirable trajectories, trap them in destitution, or facilitate pathways toward enhanced well-being. Figure 13-3 illustrates these dynamics as well as critical thresholds in livelihood trajectories.

13.2. Assessment of Climate Change Impacts on Livelihoods and Poverty

This section reviews the evidence and agreement about the relationships among climate change, livelihoods, poverty, and inequality. Building on deductive reasoning and theorized linkages about these dynamic relationships, this section draws on a wide range of empirical case studies and simulations to illustrate linkages across multiple scales, contexts, and social and environmental processes and to assess impacts of climate change. Although cases of observed impacts often rely on qualitative data and at times lack methodological clarity in terms of detection and attribution, they provide a vital evidence base for conveying these complex relationships. This section first describes observed impacts to date (Section 13.2.1) and then projected risks and impacts (Section 13.2.2).

13.2.1. Evidence of Observed Climate Change Impacts on Livelihoods and Poverty

Weather events and climate affect the lives and livelihoods of millions of poor people (IPCC, 2012b). Even minor changes in precipitation amount or temporal distribution, short periods of extreme temperatures, or localized strong winds can harm livelihoods (Douglas et al., 2008; Ostfeld, 2009; Midgley and Thuiller, 2011; Bele et al., 2013; Bryan et al., 2013). Many such events remain unrecognized given that standard climate observations typically report precipitation or temperature by month, season, or year, thus obscuring changes that shape decision making, for instance, in agriculture (Tennant and Hewitson, 2002; Barron et al., 2003; Usman and Reason, 2004; Douglas et al., 2008; Lacombe et al., 2012; Salack et al., 2012). This difficulty in detection and attribution is compounded by a lack of long-term continuous and dense networks of climate data in many LICs (UNECA, 2011). Felt experiences of events such as drought, as shown among the Sumbanese in Eastern Indonesia through phenomenological research on perceptions of climatic phenomena, such as shade and dew (Orr et al., 2012), further add to the complexity.

13.2.1.1. Impacts on Livelihood Assets and Human Capabilities

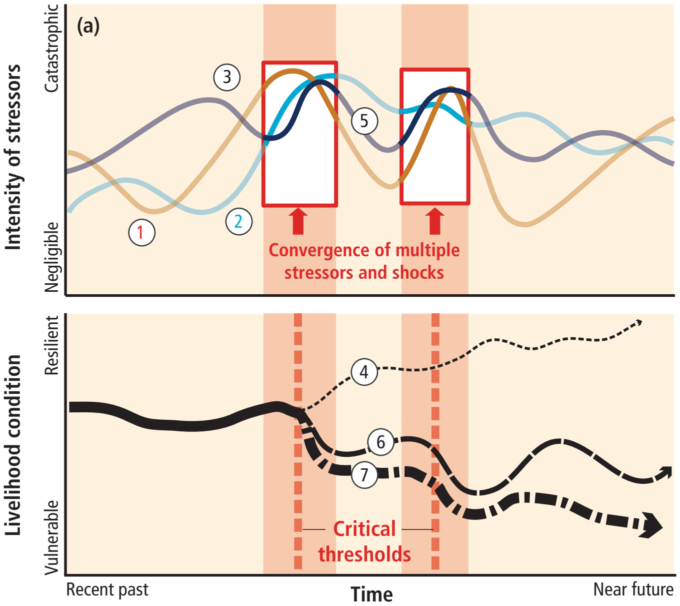
Climate change, climate variability, and extreme events interact with numerous aspects of people's livelihoods. This section presents empirical evidence of impacts on natural, physical, financial, human, and social and cultural assets (see also Chapters 22 to 29). Impacts on access to assets, albeit important, are poorly documented in the literature, as are impacts on power relations and active struggles in designing effective and relational livelihood arrangements.

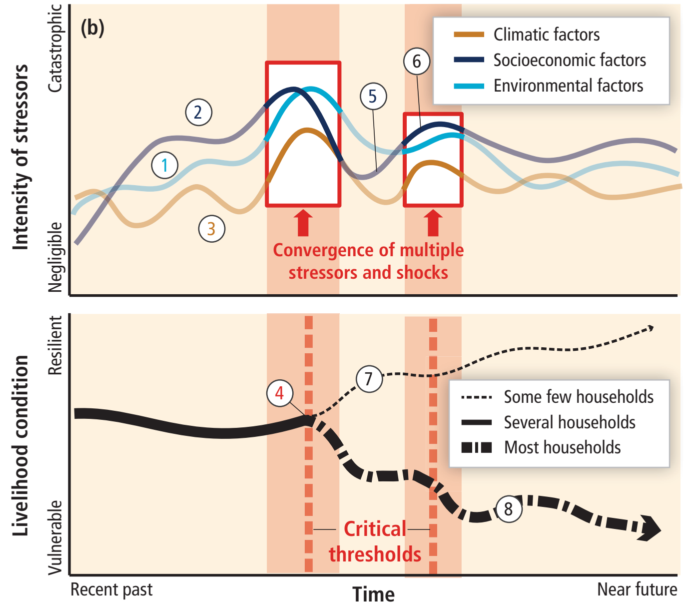
Weather events and climate affect *natural assets* on which certain livelihoods depend directly, such as rivers, lakes, and fish stocks (*robust evidence*; Thomas et al., 2007; Nelson and Stathers, 2009; Osbahr et al., 2010; Bunce et al., 2010a,b; D'Agostino and Sovacool, 2011; see also Chapters 3, 4, 5, 6, 30). During the 20th century, water temperatures increased and winds decreased in Lake Tanganyika (Adrian et al., 2009; Verburg and Hecky, 2009; Tierney et al., 2010). Since the late 1970s, a drop in primary production and fish catches, a key protein source, has been observed, and climate change may exceed the effects of overfishing and other human impacts in this area (O'Reilly et al., 2003). The Middle East and North Africa (MENA) face dwindling water resources due to less precipitation and rising temperatures combined with mounting water demand due to population and economic growth (Tekken and Kropp, 2012), resulting in rapidly decreasing water availability that, in 2025, could be 30 to 70% less per person (Sowers et al., 2011). In MENA (Sowers et al., 2011), the Andes and Himalayas (Orlove, 2009), the Caribbean (Cashman et al., 2010), Australia (Alston, 2011), and in cities (Satterthwaite, 2011), policy allocation often favors more affluent consumers, at the expense of less powerful rural and/or poor users.

Weather events and climate also erode farming livelihoods (see Chapters 7, 9), via declining crop yields (Hassan and Nhemachena, 2008; Apata et al., 2009; Sissoko et al., 2011; Sietz et al., 2012; Li et al., 2013), at times compounded by increased pathogens, insect attacks, and parasitic weeds (Stringer et al., 2007; Byg and Salick, 2009), and less availability of and access to non-timber forest products (Hertel and Rosch, 2010; Nkem et al., 2012) and medicinal plants and biodiversity (Van Noordwijk, 2010). For agropastoral and mixed crop-livestock livelihoods, extreme high temperatures threaten cattle (Hahn, 1997; Thornton et al., 2007; Mader, 2012; Nesamvuni et al., 2012); in Kenya, for instance, people may shift from dairy to beef cattle and from sheep to goats (Kabubo-Mariara, 2008).

The most extreme form of erosion of natural assets is the complete disappearance of people's land on islands and in coastal regions (McGranahan et al., 2007; Solomon et al., 2009), exacerbating livelihood risks due to loss of economic and social assets (see Chapters 5, 29; Perch and Roy, 2010). Densely populated coastal cities with high poverty such as Alexandria and Port Said in Egypt (El-Raey et al., 1999), Cotonou in Benin (Dossou and Glehouenou-Dossou, 2007), and Lagos and Port Harcourt in Nigeria (Abam et al., 2000; Fashae and Onafeso, 2011) are already affected by floods and at risk of submersion. Resettlements are planned for the Limpopo River and the Mekong River Delta (de Sherbinin et al., 2011) and small island states may become uninhabitable (Burkett, 2011).

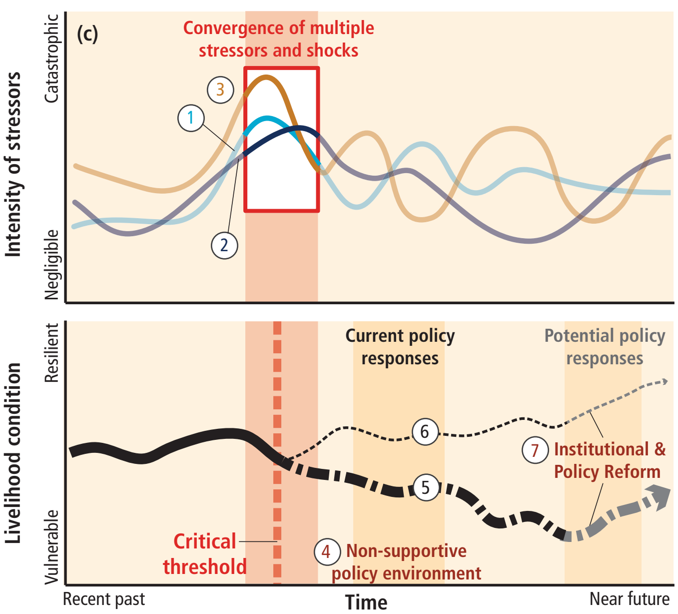
Damage to *physical assets* due to weather events and climate is well documented for poor urban settlements, often built in risk-prone

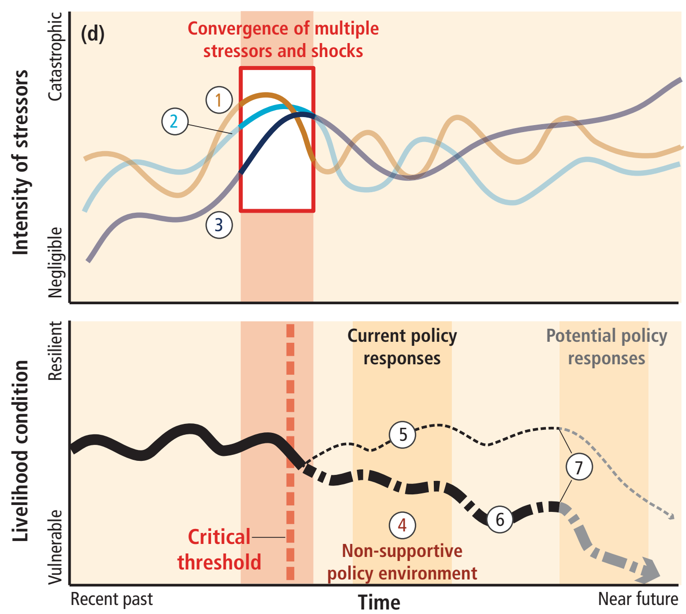




(a) Botswana's drylands (Sallu et al., 2010). Over the past 30 years, rural households have faced droughts, late onset and increased unpredictability of rainfall, and frost①, drying of Lake Xau, and land degradation②. Households responded differently to these stressors, given their financial and physical assets, diversification of and within livelihood activities, family relations, and institutional and governmental support. Despite weakening of social networks and declining livestock due to lack of water ③, distinct livelihood trajectories emerged. "Accumulators" were often able to benefit from crises, for instance through access to salaried employment ④ or new hunting quotas⑤, while "dependent" households showed a degenerative trajectory, losing more and more livelihood assets, and becoming reliant on governmental support after another period of convergent stressors⑥. "Diversifiers" had trajectories fluctuating between vulnerable and resilient states⑦.

(b) Coastal Bangladesh (Pouliotte et al., 2010). In the Sunderbans, a combination of environmental and socioeconomic factors, out of which climatic stressors appear to play only a minor role, have changed livelihoods: saltwater intrusion① due to the construction and poor management of the Bangladeshi Coastal Embankment Project, the construction of a dam in India, local water diversions② and sea level rise and storm surges③. The convergence of these stressors caused households to cross a critical threshold from rice and vegetable cultivation to saltwater shrimp farming ④. A strong export market and international donor and national government support facilitated this shift⑤. However, increasing density of shrimp farming then triggered rising disease levels⑥. Wealth and power started to become more concentrated among a few affluent families ⑦ while livelihood options for the poorer households further diminished due to lacking resources to grow crops in salinated water, the loss of grazing areas and dung from formerly accessible rice fields⑧, and rising disease levels⑥.





(c) Mountain environments (McDowell and Hess, 2012). Indigenous Aymara farmers in highland Bolivia face land scarcity, pervasive poverty, climate change, and lack of infrastructure due in part to racism and institutional marginalization. The retreat of the Mururata glacier causes water shortages ①, compounded by the increased water requirements of cash crops on smaller and smaller "minifundios" and market uncertainties ②. High temperatures amplify evaporation, and flash floods coupled with delayed rainfall cause irrigation canals to collapse③. The current policy environment makes it difficult to access loans and obtain land titles④, pushing many farmers onto downward livelihood trajectories⑤while those who can afford it invest in fruit and vegetable trees at higher altitudes ⑥. Sustained access to land, technical assistance, and irrigation infrastructure would be effective policy responses to enhance well-being⑦.

(d) Urban flooding in Lagos (Adelekan, 2010). Flooding threatens the livelihoods of people in Lagos, Nigeria, where >70 % live in slums. Increased severity in rainstorms, sea level rise, and storm surges①coupled with the destruction of mangroves and wetlands②, disturb people's jobs as traders, wharf workers, and artisans, while destroying physical and human assets. Urban management, infrastructure for water supply, and stormwater drainage have not kept up with urban growth③. Inadequate policy responses, including uncontrolled land reclamation, make these communities highly vulnerable to flooding ④. Only some residents can afford sand and broken sandcrete blocks ⑤. Livelihood conditions in these slums are expected to further erode for most households⑥. Given policy priorities for the construction of high-income residential areas, current residents fear eviction⑦.

Figure 13-3 | Illustrative representation of four case studies that describe livelihood dynamics under simultaneous climatic, environmental, and socioeconomic stressors, shocks, and policy responses – leading to differential livelihood trajectories over time. The red boxes indicate specific critical moments when stressors converge, threatening livelihoods and well-being. Key variables and impacts numbered in the illustrations correspond to the developments described in the captions.

floodplains and hillsides susceptible to erosion and landslides. Impacts include homes destroyed by flood water and disrupted water and sanitation services. Flooding has adversely affected large cities in Africa (Douglas et al., 2008) and Latin America (Hardoy and Pandiella, 2009; Hardoy et al., 2011), in predominantly dense informal settlements due to inadequate drainage, and health infrastructure (UNDP, 2011c). Yet, upper-middle- and high-income households living in flood-prone areas or high-risk slopes frequently can afford insurance and lobby for protective policies, in contrast to poor residents (Hardoy and Pandiella, 2009). Loss of physical assets in poor areas after disasters is often followed by displacement due to loss of property (Douglas et al., 2008). Increasing flash floods attributed to climate change (Sudmeier-Rieux et al., 2012) have severely damaged terraces, orchards, roads, and stream embankments in the Himalayas (Azhar-Hewitt and Hewitt, 2012; Hewitt and Mehta, 2012).

Erosion of *financial assets* as a result of climatic stressors include losses of farm income and jobs (Hassan and Nhemachena, 2008; Iwasaki et al., 2009; Alderman, 2010; Jabeen et al., 2010; Alston, 2011) and increased costs of living such as higher expenses for funerals (Gabrielsson et al., 2012). In South and Central America, more than 600 weather and extreme events occurred 2000–2013, resulting in 13,500 fatalities, 52.6 million people affected, and economic losses of US$45.3 billion (www.emdat.be). Income losses due to weather events mean less money for agricultural inputs (seeds, equipment), school tuition, uniforms, and books, and health expenses throughout the year (Thomas et al., 2007). Flooding in informal settlements in Lagos undermines job opportunities (Adelekan, 2010).

Equally important, albeit frequently overlooked, is the damage to human assets as a result of weather events and climate, such as food insecurity, undernourishment, and chronic hunger due to failed crops (*medium evidence*) (Patz et al., 2005; Funk et al., 2008; Zambian Government, 2011; Gentle and Maraseni, 2012) or spikes in food prices most severely felt among poor urban populations (Ahmed et al., 2009; Hertel and Rosch, 2010). During the Ethiopian drought (1998–2000) and Hurricane Mitch in Nicaragua (1998), poorer households tended to engage in asset smoothing, reducing their consumption to very low levels to protect their assets, whereas wealthier households sold assets and smoothed consumption (Carter et al., 2007). In such cases, poor people further erode nutritional levels and human health while holding on to their limited assets. Dehydration, heat stroke, and heat exhaustion from exposure to heat waves undermine people's ability to carry out physical work outdoors and indoors (Semenza et al., 1999; Kakota et al., 2011). Psychological effects from extreme events include sleeplessness, anxiety and depression (Byg and Salick, 2009; Keshavarz et al., 2013), loss of sense of place and belonging (Tschakert et al., 2011; Willox et al., 2012), and suicide (Caldwell et al., 2004; Alston, 2011) (see also Chapter 11 and Box CC-HS).

Finally, weather events and climate also erode *social and cultural assets*. In some contexts, climatic and non-climatic stressors and changing trends disrupt informal social networks of the poorest, elderly, women, and women-headed households, preventing mobilization of labor and reciprocal gifts (Osbahr et al., 2008; Buechler, 2009) as well as formal social networks, including social assistance programs (Douglas et al., 2008). Indigenous peoples (see Chapter 12) witness their cultural points of reference disappearing (Ford, 2009; Bell et al., 2010; Green et al., 2010).

13.2.1.2. Impacts on Livelihood Dynamics and Trajectories

Weather events and climate also affect livelihood trajectories and dynamics in livelihood decision making, often in conjunction with cross-scalar socioeconomic, institutional, or political stressors. Shifting in and out of hardship and well-being on a seasonal basis is not uncommon. To a large extent, the shifts from coping and hardship to recovery are driven by annual and interannual climate variability, but may become exacerbated by climate change. Figure 13-4 illustrates seasonal livelihood sensitivity for the Lake Victoria Basin in East Africa (Gabrielsson et al., 2012).

Shifts in livelihoods often occur due to changing climate trends, linked to a series of environmental, socioeconomic, and political stressors (*robust evidence*). Farmers may change their crop choices instead of abandoning farming (Kurukulasuriya and Mendelsohn, 2007) or take on more lucrative income-generating activities (see Figure 13-3). Uncertainty about West Africa's rainy season threatens small-scale farming and water management (Yengoh et al., 2010a,b; Armah et al., 2011; Karambiri et al., 2011; Lacombe et al., 2012). Around Mali's drying Lake Faguibine, livelihoods shifted from water-based to agro-sylvo-pastoral systems, as a direct impact of lower rainfall and more frequent and more severe droughts (Brockhaus and Djoudi, 2008). Diverse indigenous groups in Russia have changed their livelihoods as result of Soviet legacy and climate change; for example, many Viliui Sakha have abandoned cow-keeping due to youth out-migration, growing access to consumer goods, and seasonal changes in temperature, rainfall, and snow (Crate, 2013). Under certain converging shocks and stressors, people adopt entirely new livelihoods. In South Africa, higher precipitation uncertainty raised reliance on livestock and poultry rather than crops alone in 80% of households interviewed (Thomas et al., 2007). In southern Africa and India, people migrated to the coasts, switching from climate-sensitive farming to marine livelihoods (Coulthard, 2008; Bunce et al., 2010a,b). After Hurricane Stan (2005), land-poor coffee farmers in Chiapas, Mexico, turned from specializing in coffee to being day laborers and subsistence farmers (Eakin et al., 2012).

13.2.1.3. Impacts on Poverty Dynamics: Transient and Chronic Poverty

Limited evidence documents the extent to which climate change intersects with poverty dynamics, yet there is *high agreement* that shifts from transient to chronic poverty due to weather and climate are occurring, especially after a series of weather or extreme events (Scott-Joseph, 2010). Households in transient poverty may become chronically poor due to a lack of effective response options to weather events and climate, compared with more affluent households (see Figure 13-3). Often, multiple deprivations drive these shifts, with socially and economically marginalized groups particularly prone to slipping into chronic poverty. Women-headed households, children, people in informal settlements (see Chapter 8), and indigenous communities are particularly at risk, owing to compounding stressors such as lack of governmental

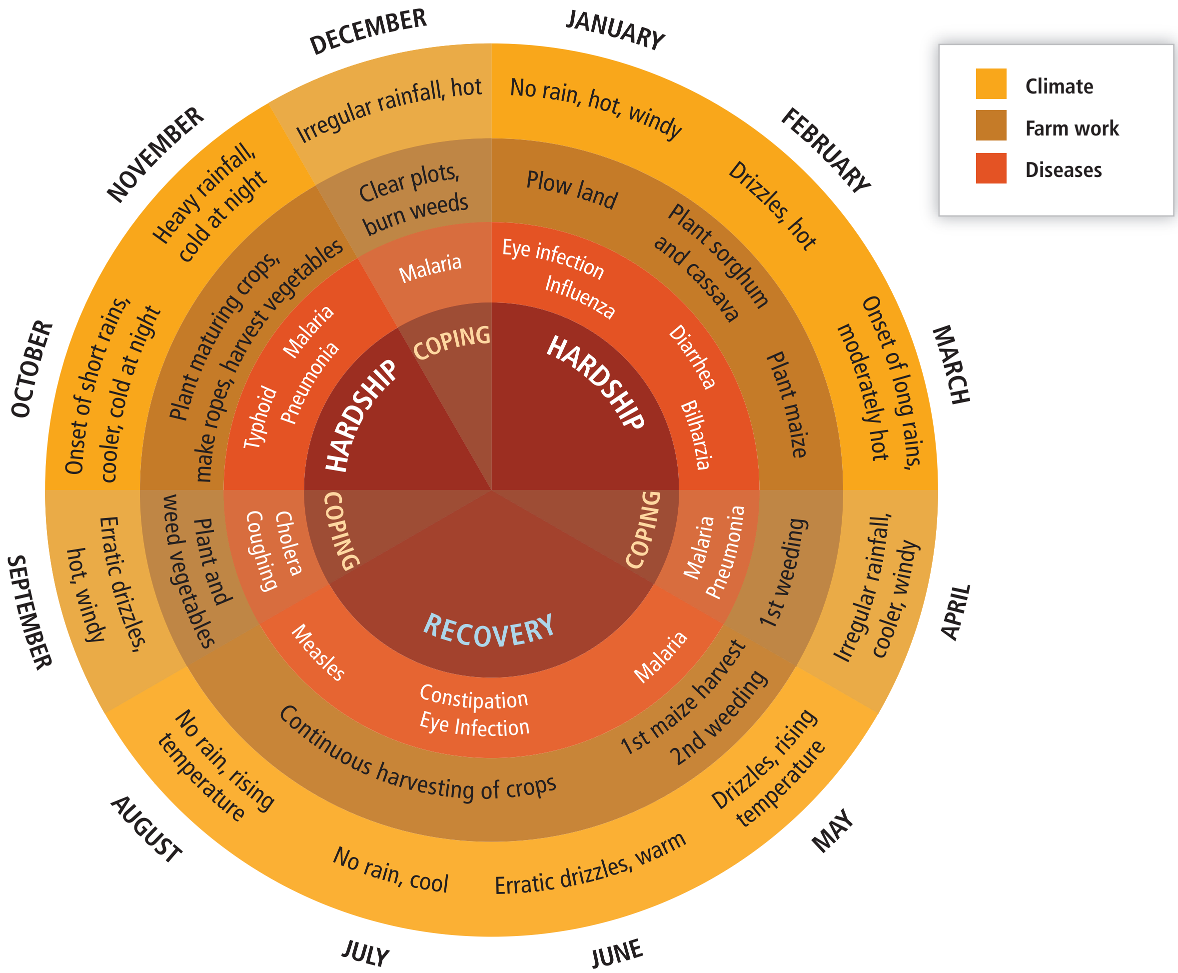


Figure 13-4 | Seasonal sensitivity of livelihoods to climatic and non-climatic stressors for one calendar year, based on experiences of smallholder farmers in the Lake Victoria Basin in Kenya and Tanzania (Gabrielsson et al., 2012).

support, urban infrastructure, and insecure land tenure (see Section 13.2.1.5 and Chapter 12).

Poor people in urban areas in LICs and MICs in Africa, Asia, and Latin America may slip from transient to chronic poverty given the combination of population growth and flooding threats in low-elevation cities and water stress in drylands (Balk et al., 2009) along with other multiple deprivations (Mitlin and Satterthwaite, 2013). Poverty shifts also occur in response to food price increases, though the strength of the relationship between weather events and climate and food prices is still debated (see Chapter 7 and Section 13.3.1.4). Poor households in urban and rural areas are particularly at risk when they are almost exclusively net buyers of food (Cranfield et al., 2007; Cudjoe et al., 2010; Ruel et al., 2010). Misselhorn (2005) showed in a meta-study of 49 cases of food insecurity in southern Africa that climatic drivers and poverty were the two dominant and interacting causal factors. Poor pastoralists have collapsed into chronic poverty when livestock assets have been lost (Thornton et al., 2007). In rural areas, restricted forest access may exacerbate poverty among already income-poor and elderly households who rely on forest resources to respond to climatic shocks (Fisher et al., 2010). Yet, many such shifts remain underexplored, incompletely captured in poverty data and adaptation monitoring. The bulk of evidence in the literature is oriented toward extreme events, rapid-onset disasters, and subsequent impacts on livelihoods and poor people's lives. Subtle changes are rarely tracked, making quantification of long-term trends and detection of impacts difficult.

13.2.1.4. Poverty Traps and Critical Thresholds

Poverty traps arise when climate change, variability, and extreme events keep poor people poor and make some poor even poorer. Yet, attribution remains a challenge. Among disadvantaged people in urban areas, poverty traps are reported especially for wage laborers who erode their financial capital due to increases in food prices (Ahmed et al., 2009; Hertel and Rosch, 2010) and for those in informal settlements exposed to floods and landslides (Hardoy and Pandiella, 2009). In rural areas, poverty traps are reported when climate change impacts on poor people persist over decades, such as through environmental degradation and recurring stress on ecosystems in the Sahel (Kates, 2000; Hertel and Rosch, 2010; Sissoko et al., 2011; UNCCD, 2011), or when people are unable to rebuild assets after a series of stresses (Eriksen and O'Brien, 2007; Sabates-Wheeler et al., 2008; Sallu et al., 2010). Poverty traps and destitution are also described in pastoralist systems, triggered through droughts, restricted mobility owing to conflict and insecurity, adverse terms of trade, and the conversion of grazing areas to agricultural land, such as for biofuel production (Eriksen and Lind, 2009; Homewood, 2009; Eriksen and Marin, 2011). Other poverty traps result from heavy debt loads due to the inability to repay loans and distress sales (Renton, 2009; Ahmed et al., 2012), persistent discrimination through legal structures and formal institutions, especially for women and other marginalized groups (Campbell et al., 2009; McDowell and Hess, 2012), and at the nexus of climate, health, and conflict (see Chapter 10).

Despite *limited evidence*, there is *high agreement* that critical thresholds, or irreversible damage (Heltberg et al., 2009), result from the convergence of various factors, many of which are not directly related to climate change. For instance, poor people often rely on social networks, including reciprocal gifts and exchanges, to protect themselves from shocks and crises such as droughts and illness (Little et al., 2006). Yet, given limited assets and ability to mobilize labor and food, particularly for smaller and women-headed households and the elderly, the exhaustion of these reciprocal ties can indicate an imminent slipping into poverty traps or chronic poverty (Pradhan et al., 2007; Osbahr et al., 2008). Injuries, disabilities, disease, psychological distress, for example from accidents during flood events, diminish poor people's main asset, labor (Douglas et al., 2008), and may plunge them into chronic poverty.

Few studies illustrate positive livelihood impacts as a result of climate change or climate-induced shocks, and they often tend to refer to more affluent and powerful constituencies. Very scarce evidence exists of poor people escaping poverty traps (see Figure 13-3). In Cameroon, though, farming communities benefit from occasional rainfall during the dry season and more food stuffs while the drying of swamps allows maize off season (Bele et al., 2013). In Lake Victoria Basin, collective action has increased as a result of HIV/AIDS and climate change, boosting social assets (Gabrielsson and Ramasar, 2012). Lessons from Hurricane Mitch (1998) in Honduras point toward more equitable land distribution and better flood preparedness that benefit the poor after disasters (McSweeney and Coomes, 2011).

13.2.1.5. Multidimensional Inequality and Vulnerability

Climate variability and change as well as climate-related disasters contribute to and exacerbate inequality, in urban and rural areas, in LICs, MICs, and HICs. Mounting inequality is not just a side effect of weather and climate but of the interaction of related impacts with multiple deprivations at the context-specific intersections of gender, age, race, class, caste, indigeneity, and (dis)ability, embedded in uneven power structures, also known as intersectionality (Nightingale, 2011; Kaijser and Kronsell, 2013; see Figure 13-5). This section illustrates how climate impacts intersect with inequality, primarily along the lines of gender, age, and indigeneity. Other chapters are referenced.

Medium evidence highlights impacts of climate stresses and extreme events on *children* (Cutter et al., 2012; O'Brien et al., 2012). Children in urban slums suffer from inadequate water supplies and malnutrition, which

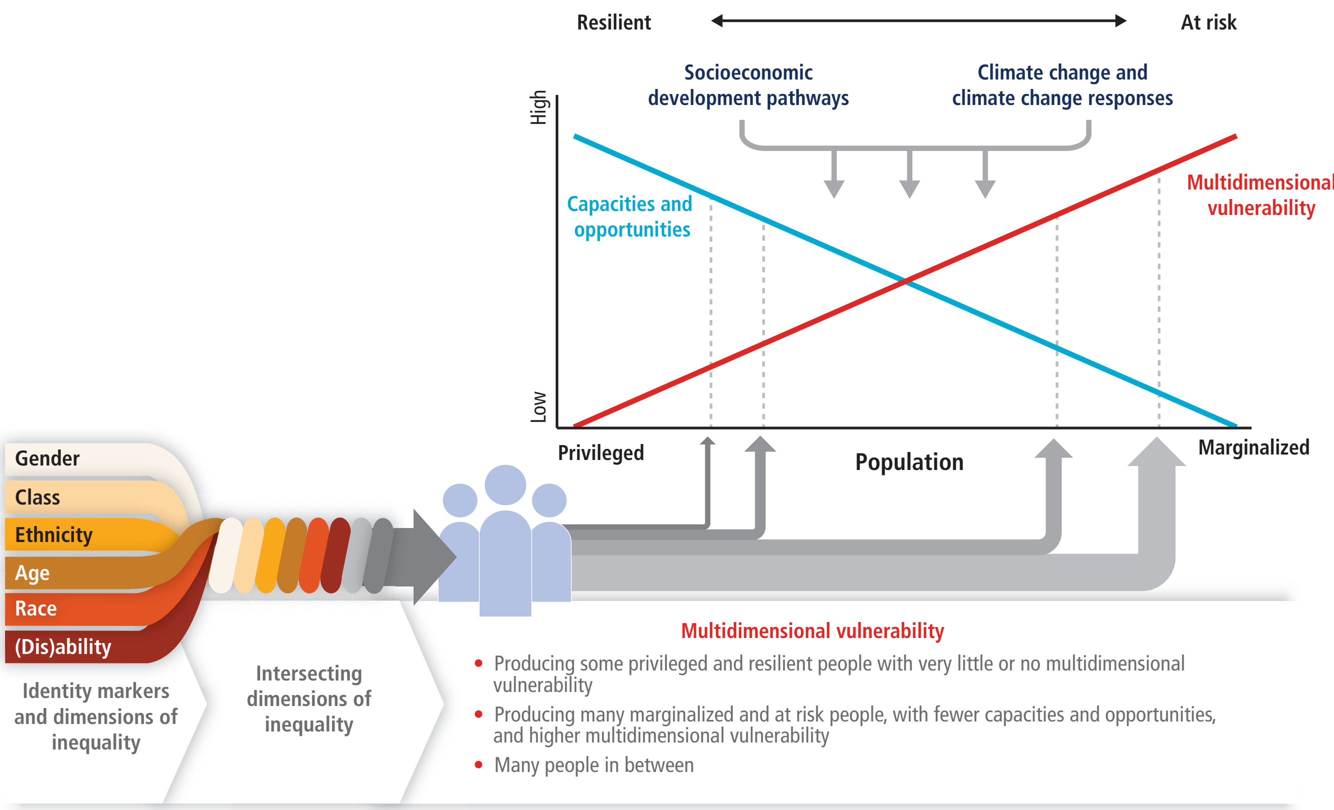


Figure 13-5 | Multidimensional vulnerability driven by intersecting dimensions of inequality, socioeconomic development pathways, and climate change and climate change responses. Vulnerability depends on the structures in society that trigger or perpetuate inequality and marginalization—not just income-poverty, location, or one dimension of inequality in itself, such as gender.

exacerbates impacts from heat stress, while excessive rain heightens water-borne diseases (Bartlett, 2008). Flood-related mortality in Nepal was twice as high for girls as for women (13.3 per 1000 girls) and also higher for boys than for men, and for young children in general six times higher than before the flood (Pradhan et al., 2007). Lower caloric intake due to two back-to-back droughts and price shocks in Zimbabwe in the 1980s resulted in physical stunting among children and reduced lifetime earnings (Alderman, 2010). In Mali, the incidence of child food poverty increased from 41% to 52% since the 2006 food price increases (Bibi et al., 2010). See Chapter 11 for more details.

Health impacts of weather events and climate differentially affect *the elderly* and *socially isolated* (Frumkin et al., 2008; see also Chapter 11). In Vietnam the elderly, widows, and disabled people, in addition to

Box 13-1 | Climate and Gender Inequality: Complex and Intersecting Power Relations

Existing ***gender inequality*** (see Box CC-GC) is increased or heightened as a result of weather events and climate-related disasters intertwined with socioeconomic, institutional, cultural, and political drivers that perpetuate differential vulnerabilities (*robust evidence*; Lambrou and Paina, 2006; Adger et al., 2007; Brouwer et al., 2007; Shackleton et al., 2007; Carr, 2008; Demetriades and Esplen, 2008; Galaz et al., 2008; Osbahr et al., 2008; Buechler, 2009; Nightingale, 2009; Terry, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Resurreccion, 2011; Heckenberg and Johnston, 2012; Zotti et al., 2012; Alston and Whittenbury, 2013; Rahman, 2013; Shah et al., 2013). While earlier studies have tended to highlight women's quasi-universal vulnerability in the context of climate change (e.g., Denton, 2002), this focus can ignore the complex, dynamic, and intersecting power relations and other structural and place-based causes of inequality (Nightingale, 2009; UNFPA, 2009; Arora-Jonsson, 2011). Moreover, the construction of economically poor women as victims denies women's agency and emphasizes their vulnerability as their intrinsic problem (MacGregor, 2010; Manzo, 2010; Arora-Jonsson, 2011).

Gendered livelihood impacts: Men and women are differentially affected by climate variability and change. The 10-year drought in Australia's Murray-Darling Basin differentially affected men and women, owing to their distinct roles within agriculture (e.g., Eriksen et al., 2010). Alston (2011) noted social disruption and depression, most profound in areas with almost total reliance on agriculture, no substitute employment, and limited service infrastructure (Table 13-1). In India, more women than men, especially women of lower castes, work as wage laborers to compensate for crop losses (Lambrou and Nelson, 2013) while in Tanzania, wealthier women hire poorer women to collect animal fodder during droughts (Muthoni and Wangui, 2013). Climate variability amplifies food shortages in which women consume less food (Lambrou and Nelson, 2013) and suffer from reproductive tract infections and water-borne diseases after floods (Neelormi et al., 2008; Campbell et al., 2009). Women farmers in the Philippines relying on high-interest loans were sent to jail after defaulting on debts following crop failure (Peralta, 2008). In Uganda, men were able to amass land after floods while droughts reduced women's non-land assets (Quisumbing et al., 2011). In Ghana, some husbands prevent their wives from cultivating individual plots as a response to gradually shifting rainfall seasonality, thereby undermining both women's agency and household well-being (Carr, 2008).

Table 13-1 | Examples of gendered climate experiences.

Experiences	Male farmers	Female farmers
Increased workload	Demanding tasks such as feeding livestock, carting water, destroying frail animals (A)	Assistance with farm tasks and working off the farm for additional income (A)
	Increased migration for wage labor, typically farther away from home (I)	Increased collection of firewood and uptake of wage labor (especially lower castes) in neighboring villages (I)
Community interactions, isolation, and exploitation	Locked into farms, loss of political power (A)	Increased interactions and caregiving work, taking care of others' health at the expense of their own (A)
	Exploitation by labor contractors when migrating (I)	Disadvantage in accessing institutional support and climate information (I)
Physical and psychological toll	Feel demonized (farmers seen as responsible for crisis), increased stress, social isolation, depression, and high suicide levels (A)	Working lives appear indefinite, resulting in increased stress (A)
	Increased anxiety to provide food and access loans and escape trap of indebtedness, increase in domestic fights, sometimes suicide (I)	Increased pressure to provide food and save some more from sale for consumption, less food intake, increase in domestic fights (I)

(A) = Australia (ten-year drought, 2003–2012), based on Alston (2011); (I) = India (climate variability and changing climatic trends), based on Lambrou and Nelson (2013).

Continued next page →

Box 13-1 (continued)

Feminization of responsibilities: Campbell et al. (2009) and Resurreccion (2011), in case studies from Vietnam, found increased workloads for both partners linked to weather events and climate, contingent on socially accepted gender roles: men tended to work longer hours during extreme events and women adopted extra responsibilities during disaster preparation and recovery (e.g., storing food and water and taking care of the children, the sick, and the elderly) and when their husbands migrated. In Cambodia, Khmer men and women accepted culturally taboo income-generating activities under duress, when rice cropping patterns shifted due to higher temperatures and more irregular rainfall (Resurreccion, 2011). Despite increased workloads for both sexes, women's extra work adds to already many labor and caring duties (Nelson and Stathers, 2009; MacGregor, 2010; Petrie, 2010; Arora-Jonsson, 2011; Kakota et al., 2011; Resurreccion, 2011; Muthoni and Wangui, 2013; Shah et al., 2013). In Nepal, shifts in the monsoon season, longer dry periods, and decreased snowfall push Dalit girls and women ("untouchable" caste) to grow drought-resistant buckwheat and offer more day labor to the high caste Lama landlords while Dalit men seek previously taboo patronage protection to engage in cross-border trade (Onta and Resurreccion, 2011). Rising male out-migration, for example, in Niger and South Africa, leave women with all agricultural tasks yet limited extra labor (Goh, 2012). Additional workloads exhaust women emotionally and physically, shown in South Africa (Babugura, 2010).

Occupational hazards: Increasing cases of heat death are reported among male workers on sugarcane plantations in El Salvador due to kidney failure (Peraza et al., 2012) and heat-related indoor work emergencies in Spain among young (<50 years) able-bodied urban men (García-Pina et al., 2008). Anecdotal evidence suggests that women tea pickers in Malawi, Kenya, India, and Sri Lanka suffer and die from heat stress as payment by quantity discourages rest breaks (Renton, 2009; see also Chapter 11 and CC-HS). In cases of male out-migration due to unsustainable rural livelihoods, women in Bangladesh face unsafe working conditions, exploitation, and loss of respect (Pouliotte et al., 2009). Yet, male out-migration could provide opportunities for women to move beyond traditionally constrained roles, explore new livelihood options, and access public decision-making space (CIDA, 2002; Fordham et al., 2011).

Emotional and psychological distress: Climate-related disasters or gradual environmental deterioration can affect women's mental health disproportionally due to their multiple social roles (UN ECLAC, 2005; Babugura, 2010; Boetto and McKinnon, 2013; Hargreaves, 2013). Increased gender-based violence within households is reported as an indirect social consequence of climate-related disasters, as well as slow-onset climate events, owing to greater stress and tension, loss and grief, and disrupted safety nets, reported for Australia (Anderson, 2009; Alston, 2011; Parkinson et al., 2011; Hazeleger, 2013; Whittenbury, 2013), New Zealand (Houghton, 2009), the USA (Jenkins and Phillips, 2008; Anastario et al., 2009), Vietnam (Campbell et al., 2009), and Bangladesh (Pouliotte et al., 2009).

Mortality: Social conditioning affects mortality for women and men. Rahman (2013) and Nellemann et al. (2011) confirm patterns of gender disparity with respect to swimming that contribute to high number of female deaths due to climate-related disasters. Restricted mobility keeps women in Bangladesh and Nicaragua waiting in risk-prone houses during floods (Saito, 2009; Bradshaw, 2010). Some disaster relief structures that lack facilities appropriate for women may contribute to increased harm and mortality (World Bank, 2010). When they are socioeconomically disadvantaged and the disasters exacerbate existing patterns of discrimination, more women die in hurricanes and floods (Neumayer and Plümper, 2007; Ray-Bennett, 2009). Yet, men experience a higher mortality rate when fulfilling culturally imposed roles as heroic life-savers (Röhr, 2006; Campbell et al., 2009; Resurreccion, 2011).

single mothers and women-headed households with small children, were least resilient to floods and storms and slow-onset events such as recurrent droughts (Campbell et al., 2009). In Australia, older citizens have shown feelings of distress as a result of familiar landscapes altered by drought, loss of home gardens, social isolation, and physical harm related to heat stress and wild fires (Pereira and Pereira, 2008; Horton et al., 2010; Polain et al., 2011). Elderly citizens in the UK may underestimate the risk and severity of heat waves through their social networks and fail to act (Wolf et al., 2010). In the USA, Europe, and South Korea, the elderly, children, and persons of lower socioeconomic status have a heightened risk of heat-related mortality (Baccini et al., 2008; Balbus and Malina, 2009; Son et al., 2012). Preliminary evidence suggests differential harm of 2012 Superstorm Sandy in New York, observed among elderly people and medically underserved populations (Pagán Motta, 2013; Teperman, 2013; Uppal et al., 2013).

Inequality and disproportionate effects of climate-related impacts also occur along the axes of *indigeneity and race*. Disproportionate climate impacts are documented for Afro-Latinos and displaced indigenous groups in urban Latin America (Hardoy and Pandiella, 2009), and indigenous peoples in the Russian North (Crate, 2013) and the Andes (Andersen and Verner, 2009; Valdivia et al., 2010; McDowell and Hess, 2012; Sietz et al., 2012). See Chapter 12 for impacts on indigenous cultures. In the USA, low-income people of color are more affected by climate-related disasters (Sherman and Shapiro, 2005; Morello-Frosch et al., 2009; Lynn et al., 2011) as demonstrated in the case of low-income African American residents of New Orleans after Hurricane Katrina (Elliott and Pais, 2006).

13.2.2. Understanding Future Impacts of and Risks from Climate Change on Livelihoods and Poverty

Future climate change, as projected through modeling, will continue to affect poor people in rural and urban areas in LICs, MICs, and HICs, alter their livelihoods, and make efforts to reduce poverty more difficult (*high confidence*). Studies reveal a broad range of impacts for the near- (2030–2040) and long-term (2080–2100) future, depending on the climatic, agro-economic, and demographic models employed, their key variables, and spatial scale, which vary from a country's agro-ecological zones to the global. Few projections take into account policy options or adaptation.

Projections emphasize the complexity and heterogeneity of future climate impacts, including winners and losers in close geographic proximity. Anticipated impacts on the poor are expected to interact with multiple stressors, most notably social vulnerability (Iglesias et al., 2011), low adaptive capacity and subsistence constraints under chronic poverty (Liu et al., 2008), weak institutional support (Menon, 2009; Xu et al., 2009; Skoufias et al., 2011a,b), population increases (Müller et al., 2011), natural resource dependence (Adano et al., 2012), ethnic conflict and political instability (Challinor et al., 2007; Adano et al., 2012), large-scale land conversions (Assuncao and Cheres, 2008; Thornton et al., 2008), and inequitable trade relations (Challinor et al., 2007; Jacoby et al., 2011).

Table 13-2 illustrates estimated risks and adaptation potentials for livelihoods and poverty dimensions until 2100.

13.2.2.1. Projected Risks and Impacts by Geographic Region

Climate change will exacerbate risks and in turn further entrench poverty (*very high confidence*). The well-known and highly referenced Wheeler data set (2011) analyzes climate risk and coping ability by country. Future increases in the frequency of extreme events are overlaid with considerable poverty, although not all poor people will be at risk. Of the 20 countries and regions most at risk, seven are LICs (Bangladesh, Ethiopia, Kenya, Madagascar, Mozambique, Somalia, and Zimbabwe), eight are LMICs (Bolivia, Djibouti, Honduras, India, Philippines, Sri Lanka, Vietnam, and Zambia), four are UMICs (China, Colombia, Cuba, and Thailand), and one is an HIC (Hong Kong). For China, Djibouti, India, Kenya, and Somalia, climate contributes between 46.4% and 87.5% to a 2008–2015 rise in national risk, compared to income and urbanization. Highest sensitivity to sea level rise by 2050, based on low-elevation coastal zones, population density, and areas of storm surge zones, is expected for India, Indonesia, China, the Philippines, and Bangladesh. India and Indonesia are projected to experience a 80% and 60% increase, respectively, in their populations at risk from sea level rise, housing a combined total of more than 58 million people most at risk by 2050; 6 million people more at risk from sea level rise in China will bring its total to 22 million, and Bangladesh's at-risk population is predicted to grow to 27 million—more than double since 2008 (Wheeler, 2011).

Specific regions at high risk are those exposed to sea level rise and extreme events and with concentrated multidimensional poverty, including pockets of poor people in LICs and MICs: mega-deltas in Bangladesh, Thailand, Myanmar, and Vietnam (Eastham et al., 2008; Wassmann et al., 2009), drylands (Anderson et al., 2009; Piao et al., 2010; Sietz et al., 2011), mountain areas (Beniston, 2003; Valdivia et al., 2010; Gentle and Maraseni, 2012; Gerlitz et al., 2012; McDowell and Hess, 2012), watersheds in the Himalayas (Xu et al., 2009), ecologically fragile areas in China (Taylor and Xiaoyun, 2012), coastal areas with severe ecosystem deterioration in eastern and southern Africa (Bunce et al., 2010a,b), and river deltas subject to resource extraction (Syvitski et al., 2009).

13.2.2.2. Anticipated Impacts on Economic Growth and Agricultural Productivity

Most projected future impact studies focus on the long-term effects of climatic changes and shocks on agricultural productivity, mainly in Africa, Asia, and Latin America. They typically examine impacts on economic growth (see also Chapter 10), changes in food prices and food security, and extrapolated changes in poverty head counts.

For future poverty head counts caused by climate change, the literature shows disagreement. For the very near future, a study by Thurlow et al. (2009) estimates that, by 2016, Zambia's poverty headcount would increase by 300,000 people under average climate variability, and by 650,000 under a worst 10-year rainfall sequence. Skoufias et al. (2011b), using 2055 predictions based on the Nordhaus (2010) RICE (Regional dynamic Integrated model of Climate and the Economy) model, state that under business-as-usual and optimal abatement, global poverty (measured at $2 per day) could be reduced by 800 million people, owing to annual and real per capita growth rate of 2.2% up to 2055. However, lower probability extreme events would reverse this trend, and mitigation under optimal abatement typically excludes people living in poverty (Skoufias et al., 2011b).

In contrast, Tubiello et al. (2008) project that, by 2080, the number of undernourished people may increase by up to 170 million, using the A2 *Special Report on Emission Scenarios* (SRES) scenarios, and up to a total of 1300 million people assuming no carbon dioxide (CO_2) fertilization.

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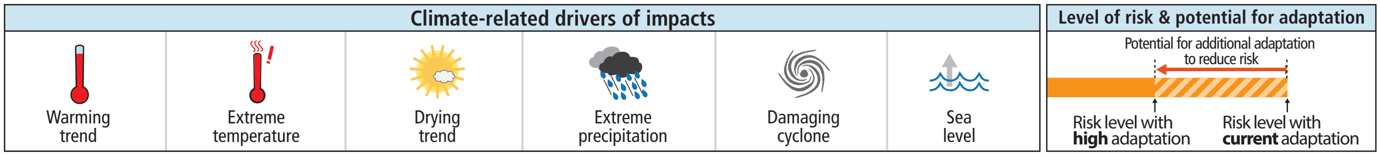
Table 13-2 | Key risks from climate change for poor people and their livelihoods and the potential for risk reduction through adaptation. Key risks are identified based on assessment of the literature and expert judgment by chapter authors, with evaluation of evidence and agreement in the supporting chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented in three timeframes: present, near-term (2030–2040), and long term (2080–2100). Near term indicates that projected levels of global mean temperature do not diverge substantially across emissions scenarios. Long term differentiates between a global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adaptive state. Bars that only show the latter indicate a limit to adaptation (see Chapter 16). Relevant climate variables are indicated by symbols. This table should not be used as a basis for ranking severity of risks.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation (Very low – Medium – Very high)
Deteriorating livelihoods in drylands, due to high and persistent poverty. Risk of reaching tipping points for crop and livestock production in small-scale farming and/or pastoralist livelihoods (*high confidence*) [13.2.1.2, 13.2.2.1, 13.2.2.3]	Adaptation options are limited owing to persistent poverty, declining land productivity, food insecurity, and limited government support due to marginalization. Rural–urban migration is a potential adaptation strategy.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	
Destruction and deterioration of assets: physical (homes, land, and infrastructure), human (health), social (social networks), cultural (sense of belonging and identity), and financial (savings) due to floods in flood-prone areas, such as low-lying deltas, coasts, and small islands (*high confidence*) [13.2.1.1, 13.2.1.3, 13.2.1.5, Box 13-1]	Adaptation options are limited for people who cannot afford relocation to safer areas. Government support and private options (e.g., insurance) are limited for people with insecure or unclear tenure.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	
Shifts from transient to chronic poverty due to persistent economic and political marginalization of poor people combined with deteriorating food security (*high confidence*) [13.2.1.3, 13.2.2.4]	Adaptation options are limited due to exclusion from markets and low government support. Policies for adaptation are unsuccessful because of failure to address persistent inequalities.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	
Declining work productivity, morbidity (e.g., dehydration, heat stroke, and heat exhaustion), and mortality from exposure to heat waves. Particularly at risk are agricultural and construction workers as well as children, homeless people, the elderly, and women who have to walk long hours to collect water (*high confidence*) [13.2.1.1, 13.2.1.5, 13.2.2.4, Box 13-1]	Adaptation options are limited for people who are dependent on agriculture and too poor to afford agricultural machinery. Adaptation options are limited in the construction sector where many poor people work under insecure arrangements. Adaptation might be impossible in certain areas in a +4°C world.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	
Declining agricultural yields, primarily in already hot climates, with severe impacts on countries and communities highly dependent on agriculture. Declining yields may cause further deterioration of assets: financial (savings), human (health), social (social networks), and cultural (sense of belonging and identity) (*high confidence*) [13.2.2.2, 13.2.2.4]	Adaptation by changing livelihoods away from agriculture is limited owing to poverty and marginalization. Adaptation strategies such as early or late planting, inter-cropping, and shifting crops bring mixed benefits and have limitations, often depending on household resources and access to seasonal forecasts and longer term projections. In a +4°C world, adaptation in agriculture is very limited.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	
Reduced access to water for rural and urban poor people due to water scarcity and increasing competition for water (*high confidence*) [13.2.1.1, 13.2.1.3, 13.2.1.5, Box 13-1]	Adaptation through reducing water use is not an option for the large number of people already lacking adequate access to safe water. Access to water is subject to various forms of discrimination, for instance due to gender and location. Poor and marginalized water users are unable to compete with water extraction by industries, large-scale agriculture, and other powerful users.		Present; Near term (2030 – 2040); Long term (2080 – 2100) 2°C; 4°C	

Projections of future climate change impacts on gross domestic product (GDP) use non-disaggregated poverty data. For instance, Mendelsohn et al. (2006) use dynamic coupled ocean-atmosphere models and market response functions to simulate the distribution of climate impacts for 2100. Independent of the climate scenarios, poor countries, mainly in Africa and Southeast Asia, will face the largest losses (0.2 to 1.2% reduction in GDP) and, under experimental models, up to 23.8% drop in GDP; in contrast, the richest quartile will encounter both positive and negative effects, ranging –0.1% to +0.2% GDP, and up to a 0.9% GDP increase under experimental models. Changes in GDP reflect climate-sensitive economic sectors, especially water and energy, with poor nations in low latitudes already facing high temperatures and thus more vulnerable to decreased agricultural productivity with increased warming. One study for the USA, using the SRES A2 scenario, projects that four climate change impacts—hurricane damage, energy costs, water costs, and real estate—are expected to cost 1.8% of the country's GDP by 2100, leading to higher household costs for basic necessities such as energy and water (Ackerman et al., 2008). Groups that spend the highest proportion of their income on these necessities will be disproportionately affected.

A growing body of literature estimates future changes in agricultural production and food prices due to climate change, variability, and extreme events (Slater et al., 2007; Thomas et al., 2007; Assuncao and Cheres, 2008; Burke et al., 2011; see Chapters 7 and 9, and Box CC-HS). Mixed trends are projected for major staples for all continents until the mid-21st century. For the near-term future, the production of coarse grains in Africa may be reduced by 17 to 22% due to climate change; well-fertilized modern seed varieties are projected to be more susceptible to heat stress than traditional ones (Schlenker and Lobell, 2010). By 2080, a major decrease in land productivity is expected for sub-Saharan Africa (–14% to –27%) and Southeast Asia (–18% to –32%), coupled with increase in water demand, while lowest risks are projected for North America, Europe, East Asia, Russia, and Australia (Iglesias et al., 2011).

13.2.2.3. Implications for Livelihood Assets, Trajectories, and Poverty Dynamics

Projections of near- and long-term climate change impacts on livelihood assets highlight the erosion of financial assets as a result of increased food prices (Ahmed et al., 2009; Seo et al., 2009; Thurlow et al., 2009; Hertel et al., 2010; Jacoby et al., 2011; Skoufias et al., 2011b), human assets due to decline in nutritional status (Liu et al., 2008), and natural assets due to lower agricultural productivity (Jones and Thornton, 2009;Thurlow et al., 2009; Skoufias et al., 2011b). They also show a substantial increase in future heat-related mortality (Basu and Samet, 2002; McGregor et al., 2006; Sherwood and Huber, 2010; Huang et al., 2011), increasing infectious disease transmission rates (Green et al., 2010), and other health impacts (see Chapter 11). Impacts on social and cultural assets have received little attention. Exceptions address losses of social identity and cultural connections with land and sea among indigenous populations threatened by sea level rise and potential relocation (Green et al., 2010) and conflicts between ethnic and/or religious groups (Adano et al., 2012; see also Chapter 12). Poor households with limited social networks will be worst off, including in places such as Nepal (Menon, 2009) and Indonesia (Skoufias et al., 2011a).

Climate change is also projected to cause shifts in livelihood trajectories. In Mali's agricultural-pastoralist transition zone, due to temperature increase and drying projected for 2025 and coupled with a 50% increase in population, shifts from rainfed millet and sorghum to semiarid, predominantly livestock subsistence are expected to expose an extra 6 million people to malnutrition, including 250,000 children suffering from stunting (Jankowska et al., 2012). Simulated probabilities of failed seasons, using current daily rainfall data and 2050 projections for the length of growing period, show transitions from cropping to livestock in other marginal cropping areas in Africa (Thomas et al., 2007; Jones and Thornton, 2009). The Met Office Hadley Centre climate prediction model 3 (HadCM3) and a high emission scenario (SRES A1F1) show that, by 2050, expanding vector populations, especially tsetse, and a greater than 20% decline in growing period, in livestock-dependent and mixed crop-livestock livelihoods in semiarid to arid Africa and Asia, combined with increasing water scarcity and stover loss due to maize substitution (Thornton et al., 2007) will stress livelihoods of poor farmers and pastoralists.

Future climate change impacts on disaggregated poverty are addressed mainly through projected changes in food prices and earnings associated with impacts on agricultural production (Schmidhuber and Tubiello, 2007). Changes in price-induced earnings lower the welfare of low-income households, particularly urban and wage-labor dependent households that use a large income share to purchase staple crops. In the near-term future, under low productivity scenarios assuming rapid temperature increase by 2030, poverty among the agricultural self-employed in 15 LICs and MICs may drop due to benefits from selling surplus production at higher prices, by as much as 40% in Chile and the Philippines; however, higher food prices may lead to a drop in national welfare, as steep as 55% in South Africa (Hertel et al., 2010). In most LICs and MICs, the poverty headcount is expected to drop in some occupational strata and increase in others; only in most African countries are yield impacts expected to be too severe to allow benefits (Hertel and Rosch, 2010). Long-term, a one-time maximum extreme dry event, simulated for 1971–2000 and 2071–2100 using the IPCC-SRES A2 scenario for 16 LICs and MICs, shows a 95 to 110% rise in poverty for urban wage groups in Malawi, Zambia, and Mexico, while self-employed farming households consolidate assets and face the smallest increase in vulnerability (Ahmed et al., 2009). By 2100, climate change would leave low-income, minority, and politically marginalized groups in California's agriculture with fewer economic opportunities, based on SRES B1 and A1FI scenarios, particularly in dairy and grape production (Cordova et al., 2006; Shonkoff et al., 2011).

13.2.2.4. Impacts on Transient and Chronic Poverty, Poverty Traps, and Thresholds

Existing projections do not provide robust evidence to estimate whether shifts from transient to chronic poverty will occur as a result of climate change, and to what extent. However, a predicted increase in the number of urban poor, especially wage laborers, suggests that a large number may shift from transient to chronic poverty owing to exposure to food price increases, or find themselves in a poverty trap, especially under scenarios with long-duration climatic shifts and prolonged droughts (Ahmed et al., 2009; Hertel et al., 2010). In Zambia, almost half of the 650,000 new poor under the worst historic 10-year period projected until 2016 are expected to be in urban areas while rural poverty remains high (Thurlow et al., 2009). In Tanzania, Ahmed et al. (2011), based on a high precipitation volatility General Circulation Model (GCM), predict up to 1.17 million new poor into the near-term future (up to 2031). Shifts in and out of poverty may occur by 2050 for small-scale coffee farmers in Central America, as suitable coffee growing areas move to higher altitudes, especially when constrained by unequal access to agro-technical and climatic information (Laderach et al., 2011).

Poor countries will face greater poverty as a result of climate change and extreme events (*medium confidence*), owing to location and low-latitude high temperatures (Mendelsohn et al., 2006) anticipated further decline in adaptive capacity combined with reductions in agricultural productivity (Iglesias et al., 2011), greater inequality and deep-rooted poverty (Jones and Thornton, 2009), and lower levels of education and large numbers of young dependents (Skoufias et al., 2011c). Although robust projections on poverty traps are lacking, they may be associated with emerging hotspots of hunger, such as those projected for Tanzania, Mozambique, and the Democratic Republic of Congo (DRC) by 2030 (Liu et al., 2008). Based on SRES scenarios, Devitt and Tol (2012) project long-term coupled climate change- and conflict-induced poverty traps for the DRC and several other sub-Saharan countries.

Some climate change projections (see Box CC-HS and WGI AR5 Chapters 11, 12, 14) indicate the possibility of large impacts that may exceed thresholds of detrimental shocks to livelihoods and poverty, unless strong adaptation and/or mitigation responses are implemented in a timely manner (Kovats and Hajat, 2008; Sherwood and Huber, 2010). Because women do most of the agricultural work, they will suffer disproportionally from heat stress; for instance, in parts of Africa, women carry out 90% of hoeing and weeding and 60% of harvesting work (Blackden and Wodon, 2006). Toward the end of the century, the risk of heat stress may become acute in parts of Africa, particularly the Sahel, and the Indian sub-continent, potentially preventing people from practicing agriculture (Patricola and Cook, 2010; Dunne et al., 2013). In the glacier-dependent Himalayan region, excessive runoff and flooding will threaten livelihoods (Xu et al., 2009). Relocation would represent a critical threshold for indigenous groups, due to sea level rise for the Torres Strait Islanders between Australia and Papua New Guinea (Green et al., 2010) and permafrost degradation and higher and seasonally erratic precipitation for the Viliui Sakha in the Russian North (Crate, 2013).

13.3. Assessment of Impacts of Climate Change Responses on Livelihoods and Poverty

Climate change responses interact with social and political processes to affect sustainable development and climate resilient pathways and in turn, livelihoods and poverty. Climate mitigation and adaptation responses include formal policies by governments, non-governmental organizations (NGOs), bilateral and multilateral organizations, as well as actions by individuals and communities. Such policy responses were designed to have positive effects on sustainable development or at least be neutral in terms of unintended side effects. Yet, much of the peer-reviewed literature scrutinizing these responses suggests otherwise. This section reviews empirical evidence of impacts of particular mitigation (Section 13.3.1) and adaptation (Section 13.3.2) responses in the context of livelihood and poverty trajectories and inequalities. Some of this evidence is preliminary as several policies are still in their infancy while other cases fail to assess multidimensional poverty or dynamic livelihood decision making in the context of climate change responses.

13.3.1. Impacts of Mitigation Responses

Many synergies between climate change mitigation policies and poverty alleviation have been identified in the literature (Klein et al., 2005; Ürge-Vorsatz and Tirado Herrero, 2012), but evidence of positive outcomes is limited. Impacts of current mitigation policies on livelihoods and poverty are controversial with polarized views on the potential of such policies for sustainable development in general and poverty alleviation in particular (Collier et al., 2008; Böhm, 2009; Hertel and Rosch, 2010; Michaelowa, 2011). This section assesses the observed and potential impacts of four climate change responses on livelihoods and poverty: the two mitigation responses most significant for poverty alleviation under the United Nations Framework Convention on Climate Change (UNFCCC), the Clean Development Mechanism (CDM) and Reduction of Emissions from Deforestation and Forest Degradation (REDD+), and two mitigation responses outside of the UNFCCC, voluntary carbon offsets and biofuel production.

13.3.1.1. The Clean Development Mechanism

The CDM (see WGIII AR5 Chapter 13) aims to promote sustainable development, thus CDM projects require approval by the host country's designated national authority. CDM projects as diverse as low-cost

Frequently Asked Questions

FAQ 13.3 | Are there unintended negative consequences of climate change policies for people who are poor?

Climate change mitigation and adaptation policies may have unintended and potentially detrimental effects on poor people and their livelihoods (the set of capabilities, assets, and activities required to make a living). Here is just one example. In part as a result of climate change mitigation policies to promote biofuels and growing concern about food insecurity in middle- and high-income countries, large-scale land acquisition in Africa, Southeast Asia, and Latin America has displaced small landholders and contributed to food price increases. Poor urban residents are particularly vulnerable to food price increases as they use a large share of their income to purchase food. At the same time, higher food prices may benefit some agricultural self-employed groups. Besides negative impacts on food security, biofuel schemes may also harm poor and marginalized people through declining biodiversity, reduced grazing land, competition for water, and unfavorable shifts in access to and control over resources. However, employment in the biofuel industry may create opportunities for some people to improve their livelihoods.

energy services in India, micro-hydro projects in Bhutan and Peru, efficient firewood use in Nigeria, and biogas digesters in China and Vietnam, are expected to generate livelihood benefits and employment, and reduce poverty among beneficiaries (UNFCCC, 2011, 2013). The secretariat's own assessment of the CDM's development benefits along 15 indicators suggested much room for improvement (UNFCCC, 2011). Most of the statistical information in official reports on CDM is based either on project documents or on surveys of project personnel rather than in-depth studies.

The assessment of the CDM in the peer-reviewed literature is more cautious and pessimistic than UNFCCC, and three reviews (Olsen, 2007; Sutter and Parreño, 2007; Michaelowa and Michaelowa, 2011) contend that the current CDM design is neither pro-poor nor contributes to sustainable development. One reason for the low performance on sustainable development criteria is that the CDM does not have any requirements for monitoring and verification of development impacts as required for emissions reductions (Boyd et al., 2009). Critiques entail obstacles and ethical dilemmas in carbon trading (Liverman, 2009; Newell and Bumpus, 2012), difficulties with implementation (Borges da Cunha et al., 2007; Minang et al., 2007; Gong, 2010), procedural limitations (Lund, 2010), and carbon offset goals favored over poverty reduction goals (Wittman and Caron, 2009). While some authors claim that the CDM undermines local and non-governmental input (Shin, 2010; Corbera and Jover, 2012), others stress its transparency, including the voices of local stakeholders (Michaelowa et al., 2012). Also, the CDM may compete with the informal sector (Newell and Bumpus, 2012) and accentuate uneven development by eroding local livelihood security (Boyd and Goodman, 2011). In a meta-analysis of 114 CDM projects, Crowe (2013) conclude that fewer than 10% of CDM projects had successfully delivered pro-poor benefits and only one of them had positive ratings on all seven criteria for pro-poor benefits. Among the most promising examples are CDM projects in India supporting community-designed plans to strengthen participation of marginalized groups (Boyd and Goodman, 2011; Subbarao and Lloyd, 2011).

13.3.1.2. Reduction of Emissions from Deforestation and Forest Degradation

Experience with REDD+ and other forest carbon projects is inadequate to permit generalizations about effects on livelihoods and poverty (Cotula et al., 2009; Hayes and Persha, 2010; Springate-Baginski and Wollenberg, 2010; see Chapter 9). A study of 20 avoided deforestation projects prior to REDD+ in Latin America, Africa, and Asia shows that only five conducted some outcome or impact assessment, revealing a lack of rigor in evaluation (Caplow et al., 2011). Despite optimism in policy analyses about the potential of REDD+ for poverty alleviation (Angelsen et al., 2009; Kanowski et al., 2011; Rahlao et al., 2012; Somorin et al., 2013), there is growing evidence and *high agreement* in the peer-reviewed literature that REDD+ may not lead to poverty alleviation and that there may even be negative consequences. Concerns include threats to the poor (Ghazoul et al., 2010; Phelps et al., 2010; Börner et al., 2011; Larson, 2011; McDermott et al., 2011; Van Dam, 2011; Mahanty et al., 2012; Neupane and Shrestha, 2012) and indigenous peoples (Shankland and Hasenclever, 2011). Latent negative impacts include exclusion of local people from forest use, and loss of local ownership in documenting the state of forests due to external monitoring and verification mechanisms (Gupta et al., 2012; Pokorny et al., 2013). Benefit flows may be unevenly distributed with regards to ethnicity (Krause and Loft, 2013), gender (Peach Brown, 2011; UN-REDD, 2011), or simply not target the poor (Hett et al., 2012). The absence of a global REDD+ mechanism means that progress on REDD+ may occur as much through voluntary bilateral and public-private processes as through multilateral, regulatory requirements (Agrawal et al., 2011). Positive future benefits for poor people from REDD+ will require attention to tenure and property rights, gender interests, and community engagement (Danielsen et al., 2011; Mustalahti et al., 2012).

The 2010 Cancun Agreements highlight safeguards for governments to observe in REDD+ implementation, such as respect for the interests, knowledge, rights, and sustainable livelihoods of communities and indigenous peoples. If these safeguards will be observed in practice is unclear owing to the early implementation state of REDD+ in most countries as well as the uncertainty of the future of the global carbon market (Lohmann, 2010; Savaresi, 2013).

13.3.1.3. Voluntary Carbon Offsets

The voluntary carbon offset (VCO) market is significant from a livelihoods and poverty perspective because it typically targets smaller projects and may be better at reaching poor communities (Estrada and Corbera, 2012), though it is modest in size compared to the regulated market (approximately 1%). Also, those involved in the VCO market, namely individuals, companies, organizations, and countries that have not ratified the Kyoto Protocol, are often more willing to pay for carbon offsets with co-benefits such as poverty alleviation (MacKerron et al., 2009).

Activities under VCO are dominated by renewable energy, primarily wind power (30%), forestation projects including REDD+ (19%), and methane destruction in landfills (7%) (Peters-Stanley and Hamilton, 2012). It is too early to tell whether these VCO projects are successful in terms of poverty alleviation and other social goals, and results to date are highly mixed (Jindal et al., 2008; Swallow and Meinzen-Dick, 2009; Jindal, 2010; Estrada and Corbera, 2012; Stringer et al., 2012). Reported benefits include livelihood diversification, increased disposable income, biodiversity conservation, and strengthening local organizations, while exacerbated inequalities and loss of access to local resources are known negative impacts (Estrada and Corbera, 2012). A study in Kenya, Senegal, and Peru shows reduced losses of soil fertility in three soil carbon sequestration projects, but also the inability of the poorest farmers to participate and only marginal impacts on poverty reduction (Antle and Stoorvogel, 2009). Out of 78 projects in 23 countries in sub-Saharan Africa, only one promoted local social, economic, and environmental benefits while the rest focused mainly on efficiency of emission reductions (Karavai and Hinostroza, 2013).

13.3.1.4. Biofuel Production and Large-Scale Land Acquisitions

Biofuel production, often linked to transnational large-scale land acquisitions (LSLA), is a near-term climate change mitigation response that raises two major livelihood and poverty concerns: food price increases and dispossession of land (see Chapters 4, 9). LSLA have soared since 2008 (Von Braun et al., 2009; Borras Jr. et al., 2011a; Deininger et al., 2011), partly linked to climate change responses (*medium evidence*, *high agreement*). Biofuel production is considered the primary driver, but there may be links to climate change through high food prices (Daniel, 2011), food insecurity (Robertson and Pinstrup-Andersen, 2010; Rosset, 2011; Sulser et al., 2011), and carbon markets potentially raising land prices, for example, REDD+ (Cotula et al., 2009; Zoomers, 2010; Anseeuw et al., 2012). LSLA global targets are biofuels (40%), food (25%), and forestry (3%), with much regional variation (Anseeuw et al., 2012). The IPCC special report on renewable energy highlighted the uncertainties around the role of biofuels in food price increases and risks of deteriorating food security with future deployment of bioenergy (Edenhofer et al., 2011).

Increasing demand for biofuels shifts land from food to fuel production, which may increase food prices (Collier et al., 2008) disproportionally affecting the poor (Von Braun and Ahmed, 2008; Bibi et al., 2010; Ruel et al., 2010). Despite high agreement that biofuel production plays a role in food prices, little consensus exists on the size of this influence (Aksoy and Isik-Dikmelik, 2008; Elobeid and Hart, 2008; Mitchell, 2008; Von Braun and Ahmed, 2008; Baffes and Haniotis, 2010; Ajanovic, 2011; Condon et al., 2013). Some studies link the 2007/2008 price spike to speculation in agricultural futures markets (Runge and Senauer, 2007; Ghosh, 2010) driven partly by potential future profits from biofuels while their role was relatively less important in the 2010/2011 price spike (Trostle et al., 2011).

LSLA have also triggered a land rush in LICs, which affects livelihood choices and outcomes, with some distinct gender dimensions (Chu, 2011; De Schutter, 2011; Julia and White, 2012; Peters, 2013). New competition for land dispossesses smallholders, displaces food production, degrades the environment, and pushes poor people onto more marginal lands less adaptable to climatic stressors (Cotula et al., 2009; Borras Jr. et al., 2011a; Rulli et al., 2013; Weinzettel et al., 2013). The expansion of bioenergy, and biofuels in particular, increases the corporate power of international actors over governments and local actors with harmful effects on national food and agricultural policies (Dauvergne and Neville, 2009; Glenna and Cahoy, 2009; Hollander, 2010; Mol, 2010; Fortin, 2011; Jarosz, 2012), further marginalizing smallholders (Ariza-Montobbio et al., 2010; De Schutter, 2011; Neville and Dauvergne, 2012) and indigenous peoples (Montefrio, 2012; Obidzinski et al., 2012; Manik et al., 2013; Montefrio and Sonnenfeld, 2013). There is growing apprehension that increased competition for scarce land undermines women's access to land and their ability to benefit economically from biofuel investment (Arndt et al., 2011; Chu, 2011; Molony, 2011; Behrman et al., 2012; Julia and White, 2012; Perch et al., 2012). Concerns differ somewhat among regions, with the greatest risk for negative outcomes for smallholders in Africa (Daley and Englert, 2010; Borras et al., 2011b).

Mainstream economic modeling offers optimism that biofuels may boost investment, employment, and economic growth in LICs such as Mozambique (Arndt et al., 2009) and MICs such as India (Gopinathan and Sudhakaran, 2011) and Thailand (Silalertruksa et al., 2012) yet limited evidence exists on potential benefits being realized. A major government initiative to promote jatropha cultivation in India has failed (Kumar et al., 2011) and in some cases has left rural people worse off (Bastos Lima, 2012), whereas in Malawi it offered supplemental livelihood opportunities (Dyer et al., 2012). Even though income and employment in Brazil may have increased due to ethanol production (Ferreira and Passador, 2011), structural inequalities in the sector remain (Peskett, 2007; Hall et al., 2009; Bastos Lima, 2012). Biofuel production in itself will not transform living conditions in rural areas without being integrated into development policies (Hanff et al., 2011; Dyer et al., 2012; Jarosz, 2012).

13.3.2. Impacts of Adaptation Responses on Poverty and Livelihoods

Local responses to climate variability, shocks, and change have always been part of livelihoods (Morton, 2007). Formal policy responses to climate change, however, have developed more recently as the urgency of adaptation, in addition to mitigation, became a clear international policy mandate (Pielke Jr. et al., 2007). Even well-intentioned adaptation projects (see Chapters 14 to 16) and efforts may have unintended and sometimes detrimental impacts on livelihoods and poverty, and may exacerbate existing inequalities. This section assesses the near-term effects of autonomous and planned adaptation and formal insurance schemes on the livelihoods of poor populations. Because adaptation policies and projects are relatively recent, understanding of their long-term effects is very limited.

13.3.2.1. Impacts of Adaptation Responses on Livelihoods and Poverty

Autonomous adaptation strategies—such as diversification of livelihoods (Smith et al., 2000; Mertz et al., 2009), migration (McLeman and Smit, 2006; Tacoli, 2009; see Chapter 12), storage of food (Smit and Skinner, 2002; Howden et al., 2007), communal pooling (Linnerooth-Bayer and Mechler, 2006), market responses (Halstead and O'Shea, 2004); and saving, credit societies, and systems of mutual support (Andersson and Gabrielsson, 2012)—have been found to have positive effects on poverty reduction in certain contexts, or at least prevent further deterioration due to weather events and climate, especially when supported by policy measures (Adger et al., 2003; Urwin and Jordan, 2008; Stringer et al., 2009). Yet, some autonomous strategies such as diversification and storage are often unavailable to the poorest, who lack the required resources or surplus (Smithers and Blay-Palmer, 2001; Osbahr et al., 2008; Seo, 2010) or require more labor-intensive practices that undermine people's health and may push them over a poverty threshold (Eriksen and Silva, 2009). Moreover, autonomous adaptation strategies can increase vulnerability for others or be subject to local elite capture (McLaughlin and Dietz, 2008; Eriksen and Silva, 2009; Bhattamishra and Barrett, 2010). Men's migration in Northern Mali, for example, increases the workload of the rest of the family, especially women, and reduces children's school attendance (Brockhaus et al., 2013). There is no evidence regarding the impacts of autonomous responses on people living in poverty in MICs and HICs.

Few rigorous studies about pilot adaptation projects exist outside of organizations' own assessments (Mapfumo et al., 2010; Nkem et al., 2011) or evaluations of how planned adaptation was implemented or integrated into development (Gagnon-Lebrun and Agrawala, 2006; Gigli and Agrawala, 2007). An assessment of the only completed Global Environment Facility/World Bank (GEF/WB)-funded adaptation project, in the Caribbean, Colombia, and Kiribati, did not directly appraise the effects on poverty and livelihoods due to scarce baseline poverty data. Other projects, such as in India's Karnataka Watershed, are said to have increased agricultural productivity, income, and employment, benefiting the poorest and landless and improving equity (IEG, 2012). National Action Plans of Adaptation tend to overemphasize technological and infrastructural measures while often overlooking poor people's needs, gender issues, and livelihood and adaptation strategies (Agrawal and Perrin, 2009; Perch, 2011).

13.3.2.2. Insurance Mechanisms for Adaptation

Insurance mechanisms (see Glossary and Chapter 10) reflect the tendency that some formal adaptation measures reach the wealthier more easily while prohibitive costs may prevent poor people from accessing such mechanisms. Nonetheless, public and private insurance systems have been proposed by the World Bank and UNFCCC as an adaptation strategy to reduce, share, and spread climate change-induced risk and smooth consumption, especially among poor households (Mechler et al., 2006; Hertel and Rosch, 2010; Akter et al., 2011; Benson et al., 2012). Formal insurance schemes can potentially provide a way out of poverty traps (Barnett et al., 2008) caused by a household's process to rebuild assets after climate shocks over years (Dercon, 2006; Hertel and Rosch, 2010).

Poor people tend not to be insured via formal institutions, though strategies such as risk spreading, social networks, local credit, asset markets, and dividing herds between kin act as informal risk management mechanisms (Barnett et al., 2008; Giné et al., 2008; Pierro and Desai, 2008; De Jode, 2010; Hertel and Rosch, 2010). Unable to access insurance, they often invest in low-risk, low-return livelihood activities, which makes asset accumulation to escape chronic poverty very difficult (Elbers et al., 2007; Barnett et al., 2008). As a response, new insurance mechanisms such as micro-insurance directed at low-income people and weather index insurance for crops and livestock (see also Chapter 10) have emerged, showing mixed results (Barnett et al., 2008; Mahul et al., 2009; Akter et al., 2011; Matsaert et al., 2011; Biener and Eling, 2012).

Experiences from South Asia and several African countries illustrate positive effects of micro-insurance on investment, production, and income under drought and flood risk, including possible longer-term impacts on future income-earning activities and health, although affordability may limit the potential for the poorest (Yamauchi et al., 2009; Hochrainer-Stigler et al., 2012; Karlan et al., 2012; Tadesse and Brans, 2012). There is emerging evidence that weather index insurance can be specifically designed to reach the people usually uninsurable, for example, by premium-for-work arrangements. In such arrangements farmers provide labor and in return get an insurance certificate against rain failure in a crucial growth period for their staple crops (Brans et al., 2011). Slow uptake of insurance among poor people may be related to farmers not fully understanding the schemes' merits and function or not trusting that payouts will come (Giné and Yang, 2009; Patt et al., 2010).

13.4. Implications of Climate Change for Poverty Alleviation Efforts

This section assesses how climate change may affect efforts to alleviate poverty. Evidence from observed impacts and projections highlight both challenges and opportunities. The section builds on the findings from Sections 13.1 to 13.3 and stresses the need to take into account the complexity of livelihood dynamics, multidimensional poverty, and intersecting inequalities to successfully navigate climate-resilient development pathways (see Glossary).

Observed impacts of weather events and climate on livelihoods and poverty and impacts projected from the subnational to the global level suggest that livelihood well-being, poverty alleviation, and development are already undermined and will continue to be eroded into the future (*high confidence*). Climate change will slow down the pace of poverty reduction, jeopardize sustainable development, and undermine food security (*high confidence*; Hope, 2009;Stern, 2009; Thurlow et al., 2009; Iglesias et al., 2011; Skoufias et al., 2011b). Currently poor and food-insecure regions will continue to be disproportionately affected into the future (*high agreement*; Challinor et al., 2007; Assuncao and Cheres, 2008; Lobell et al., 2008; Liu et al., 2008; Thornton et al., 2008; Jones and Thornton, 2009; Menon, 2009; Nordhaus, 2010; Burke et al., 2011; Jacoby et al., 2011; Skoufias et al., 2011a; Adano et al., 2012). Poorer countries will experience declining adaptive capacity, which will hamper development (*high confidence*). Posey (2009) flags lower adaptive capacities in communities with concentrations of racial minorities and low-income households than in more affluent areas, due to marginalization and multidimensional inequality. Iglesias et al. (2011) project continental disparities in agricultural productivity under progressively severe climate change scenarios with highest risks for Africa and Southeast Asia. Although there is *high agreement* about the heterogeneity of future impacts on poverty, few studies consider more diverse climate change scenarios (Skoufias et al., 2011b) or the potential of 4°C and beyond (New et al., 2011). The World Bank (2012b, p. 65) states that "climate change in a four degree world could seriously undermine poverty alleviation in many regions."

13.4.1. Lessons from Climate-Development Efforts

Two key models have attempted to integrate climate and poverty concerns into development efforts: mainstreaming adaptation into development priorities and pro-poor adaptation (see Chapters 14 to 16, 20). Lessons from "adaptation as development," in which development is seen as the basis for adaptation, and "adaptation plus development," in which development interventions address future climate threats (Ayers and Dodman, 2010), typify the disagreement in policy spheres about what sustainability constitutes (Le Blanc et al., 2012) and the practical gulf between climate change policy and development spheres (Ayers and Dodman, 2010). To date, observed and projected climate change impacts are not systematically integrated into poverty reduction programs, although such integration could result in substantial resilience to covariate and idiosyncratic shocks and stresses (Brans et al., 2011; Béné et al., 2012). At the same time, science and policy emphasis on rapid-onset events, sectoral impacts, and poverty statistics has diverted attention from threats to sustainability and resilient pathways. Even

Box 13-2 | Lessons from Social Protection, Disaster Risk Reduction, and Energy Access

Social protection (SP): Considerable challenges emerge at the intersection of climate change adaptation, disaster risk reduction, and social protection. SP programs include public and private initiatives that transfer income or assets to poor people, protect against livelihood risks, and raise the social status and rights of the marginalized (see Glossary). Cash transfer programs are among the principal instruments used by governments for poverty alleviation (Barrientos and Hulme, 2009; Barrientos, 2011; Niño-Zarazúa, 2011). There is *medium agreement* among scholars and practitioners that SP helps people in chronic poverty reduce risk and protect assets during crises (Devereux et al., 2010, 2011; Barrientos, 2011; Dercon, 2011). At the regional and municipal level, SP often fails to address local government capacity to ensure risk reduction by providing water, sanitation, drainage, health care, and emergency services. Also, SP does not intentionally strengthen local collective capacity to proactively address climate change risks and take action (Satterthwaite and Mitlin, 2013).

SP that supports pro-poor climate change adaptation and disaster risk reduction by strengthening the resilience of vulnerable populations to shocks is labeled "adaptive social protection" (ASP) (Davies et al., 2009). ASP should be understood as a framework rather than a package of specific measures. ASP has almost exclusively focused on LICs and some MICs with very little attention to poor people in HICs. Few studies exist on the effectiveness of ASP for addressing incremental climatic changes and rapid-onset events, and the changing nature of climate risks as part of dynamic livelihood trajectories (Heltberg et al., 2009; Arnall et al., 2010; Bee et al., 2013). The Productive Safety Net Program in Ethiopia, for instance, had positive effects on household food consumption and asset protection (Devereux et al., 2006; Slater et al., 2006). Yet, this and programs such as Brazil's *Bolsa Familia* and *Bolsa Verde* (UNDP, 2012) offer few concrete pathways to tackling systemic vulnerabilities and inequalities that inhibit effective responses to severe shocks, though they stress the role of local governments in addressing long-term livelihood security and well-being in addition to short-term disaster relief (Gilligan et al., 2009; Conway and Schipper, 2011; Béné et al., 2012; UNDP, 2012). Local governments in urban contexts have limited capacities to address livelihood security, but more scope to increase resilience through risk-reducing infrastructure (Satterthwaite and Mitlin, 2013).

Disaster risk reduction (DRR): The development and application of DRR (see Glossary) has been among the most important routes for highlighting risks of extreme weather among local governments and civil society, and came to the fore as the concentration of disaster deaths from extreme weather in LICs and MICs became evident (UNISDR, 2009, 2011). However, the accumulated effect of several small-scale events is often more damaging than large-scale ones (Aryal, 2012). DRR is now increasingly employed as an adaptation measure, for example, through community-based climate risk reduction (Tompkins et al., 2008; McSweeney and Coomes, 2011; Meenawat and Sovacool, 2011; IPCC, 2012b) and has helped identify DRR roles for local governments (IFRC, 2010). Yet, sometimes disaster management-oriented adaptation can favor property and investments of the relatively richer and divert attention and funding from measures that address disadvantaged people, as suggested in a case study of Vietnam (Buch-Hansen, 2013). The effectiveness of DRR in supporting pro-poor climate change adaptation will depend on governance structures to address changing risk contexts in policies and investments while responding to the needs and priorities of their low-income population. Lessons learned from Hurricane Katrina and the Tōhoku earthquake and tsunami showcase the multiplier effect of a disaster on top of underlying structural inequalities. Their persistence years later, as witnessed with Katrina (Schwartz, 2007; Zottarelli, 2008; Fussell et al., 2010) further stresses the need for expanded analyses beyond disaster events themselves and the recognition of the many factors that perpetuate the vicious cycle of poverty, multidimensional deprivation, and inequality.

Energy access: Energy is critical for rural development (Barnes et al., 2010; Kaygusuz, 2011, 2012) and for alleviation of urban poverty (Parikh et al., 2012). One proposed climate-resilient pathway is to boost renewable energy use, which could increase energy access for billions of people currently without access to safe and efficient energy while cutting greenhouse gas emissions from rising non-renewable energy consumption (Casillas and Kammen, 2010; Edenhofer et al., 2011). Benefits include better health (see also Chapter 11), employment, and cost savings relative to fossil fuels (Edenhofer et al., 2011; Jerneck and Olsson, 2012).

where legal reforms to secure the rights of poor people exist, as in Mexico's Climate Law, inequalities persist (MacLennan and Perch, 2012). Without addressing the climatic, social, and environmental stressors that shape livelihood trajectories, including poverty traps (see Figure 13-2), and the underlying causes of poverty, persistent inequalities, and uneven resource access and institutional support, adaption efforts and policies will be nothing more than temporary fixes. Poverty alleviation alone will not necessarily lead to more equality (Pogge, 2009; Milanovic, 2012). Box 13-2 provides insight into three examples.

13.4.2. Toward Climate-Resilient Development Pathways

Given the multiple challenges at the climate-poverty-development nexus, debates increasingly focus on transforming the development pathways themselves toward greater social and environmental sustainability, equity, resilience, and justice, calling for a fundamental shift toward near- and long-term climate-resilient development pathways (see Chapter 20). This perspective acknowledges the shortcomings in dominant global development pathways, above all rising levels of consumption and emissions, privatization of resources, and limited capacities of local governments and civil society to counter these trends (Pelling, 2010; Eriksen et al., 2011; O'Brien, 2012; UN, 2012a).

At Rio+20 in 2012, an Open Working Group was created by the UN General Assembly to develop Sustainable Development Goals (SDGs) building on the Millennium Development Goals (MDGs), which are criticized for not explicitly addressing the root causes of poverty, inequality, or climate change (Melamed, 2012; UN, 2012b) and the anticipated failure to reach MDG 1 (eradicate extreme poverty and hunger by 2015), with or without climate change (Tubiello et al., 2008). Early SDG debates reveal a stronger focus on eradicating extreme poverty and environmental problems facing poor people (UN, 2012a). This framing of development acknowledges shared global futures that require collective action from the richest, not merely promoting welfare for the poorest, to address both climate change and poverty (Ayers and Dodman, 2010; UN, 2012a,b). Little information exists to date to project how these SDGs will support climate-resilient development pathways. Formulating goals, however, will not suffice unless the global institutional framework for sustainable development is radically reformed (Biermann et al., 2012).

Paying attention to dynamic livelihoods and multidimensional poverty and the multifaceted impacts of climate change and climate change responses is central to achieving climate-resilient development pathways (see Chapter 20). Evidence from Sections 13.2 and 13.3 suggests that increasing global inequality, new poverty in MICs and HICs, and more people shifting from transient to chronic poverty overlaid with business-as-usual development and climate policies will bring poor and marginalized people precariously close to the two most undesirable future scenarios as conceptualized in the shared socioeconomic pathways (SSPs) (see Chapter 1): social fragmentation (fragmented world) and inequality (unequal world). At the community level, inadequate governance structures and elite capture often propel less affluent households into deeper poverty. There is *high agreement* among scholars of global governance that fragmentation also exists at the level of the global climate regime (Biermann, 2010; Roberts, 2011; Mol, 2012), rooted in entrenched inequalities (Parks and Roberts, 2010). The extent to which fragmentation promotes positive or negative outcomes of climate and development goals is contested, ranging from polycentric governance modes (Ostrom, 2010) to conflictive fragmentation (Biermann et al., 2009; Mittelman, 2013). Evidence from this chapter suggests that, in order to move toward the mid- and long-term SSP 1 (sustainability), a fundamental rethinking of poverty and development will need to emphasize equity among poor and non-poor people to collectively address greenhouse gas emissions and vulnerabilities while striving toward a joint, just, and desirable future.

13.5. Synthesis and Research Gaps

Previous IPCC reports have stated that climate change would cause disproportionally adverse effects for the world's poor people. However, they presented a rather generalized view that all poor people were vulnerable, in contrast to earlier scientific studies highlighting vulnerability as contextual with variation over time and space. This chapter is devoted to exploring poverty in relation to climate change, a new theme in the IPCC. It uses a livelihood lens to assess the interactions between climate change and the multiple dimensions of poverty, not just income poverty. This lens also reveals how inequalities perpetuate poverty, and how they shape differential vulnerabilities and in turn the differentiated impacts of climate change on individuals and societies. This chapter illustrates that climate change adds an additional burden to poor people and their livelihoods, acting as a threat multiplier. Moreover, it emphasizes that climate change may create new groups of poor people, not only in low-income countries but also in middle- and high-income countries. Neither alleviating poverty nor decreasing vulnerabilities to climate change can be achieved unless entrenched inequalities are reduced. This chapter concludes that climate change policy responses reviewed in this chapter often do not benefit poor people, and highlights lessons for climate-resilient development pathways.

Eight major research gaps are identified with respect to the observed and projected impacts of climate change and climate change responses:

- Poverty dynamics are not sufficiently accounted for in current climate change research. Most research as well as poverty measurements remain focused on only one or two dimensions of poverty. Insufficient work assesses the distribution of poverty at the level of households, spatial and temporal shifts, critical thresholds that plunge some transient poor into chronic poverty, and poverty traps, in the context of climatic and non-climatic stressors. Many of these dynamics remain hidden, incompletely captured in poverty statistics and disaster and development discourses. Key assumptions in many economic models (e.g., constant within-country distribution of per capita income over time, linear relationship between economic growth and poverty headcounts) are ill suited to capture local and subnational poverty dynamics, confounding projections of future poverty levels.
- Though an abundance of studies exists that explore climate change impacts on livelihoods, the majority does not focus on continuous struggles and trajectories but only offers snapshots. An explicit analysis of livelihood dynamics would more clearly reveal how people respond to a series of climatic stressors and shocks over time.

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- Few studies examine how structural inequalities, power imbalances, and intersecting axes of privilege and marginalization shape differential vulnerabilities to climate change. Although there is growing literature on climate change and gender as well as on indigeneity, other axes such as age, class, race, caste, and (dis)ability, remain underexplored. Understanding how simultaneous and intersecting inequalities determine climate change impacts shows which particular drivers of vulnerability are at play in one context, while absent in another.
- Very limited research examines climate change impacts on poor people and livelihoods in middle- to high-income countries. Despite mounting evidence of observed impacts of climatic events on the poor in MICs and HICs, as documented for the European heat wave, Hurricane Katrina in the USA, and the 10-year drought in Australia, the majority of research on the poverty-climate nexus remains focused on the poorest countries.
- There remains a lack of rigorous data collection and analysis regarding small-scale disasters, that is, those that go unnoticed because of their limited extent, but whose accumulated effect may exceed large-scale disasters. This gap leads to significant underestimation of lived experiences with climate change, in which particular loss and harm remain largely undetected. There is a need for more climatology research informed by the needs of poor people and vulnerable livelihoods, for instance on the effects of changing winds as a combined result of climate and land cover change, and their effects on increasing evaporation and water availability.
- Not enough consideration is given to extreme stressors and shocks, for example, under potential global mean warming of +4°C and beyond, underestimating impacts on poor and marginalized people and limits to adaptation.
- There is a lack of in-depth research on the direct and indirect effects of mitigation and adaptation climate-related policies such as CDM, REDD+, biofuels, and insurance on livelihoods, poverty, and inequality. More in-depth research has the potential to improve the capacity of these policies to benefit poor people.
- Limited understanding exists of how poverty alleviation and more equality between the poor and the non-poor are best built into climate-resilient development pathways to strive toward a just and desirable future for all.

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14

Adaptation Needs and Options

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Executive Summary

Since the Fourth Assessment Report (AR4), the framing of adaptation has moved further from a focus on biophysical vulnerability to the wider social and economic drivers of vulnerability and people's ability to respond (*robust evidence*, *high agreement*). These drivers include the gender, age, health, social status, and ethnicity of individuals and groups, and the institutions in place locally, nationally, regionally, and internationally. Adaptation goals are often expressed in a framework of increasing resilience, which encourages consideration of broad development goals, multiple objectives, and scales of operation, and often better captures the complex interactions between human societies and their environment. The convergence between adaptation and disaster risk management has been further strengthened since AR4, building on the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX). {14.1-3}

Adaptation needs arise when the anticipated risks or experienced impacts of climate change require action to ensure the safety of populations and the security of assets, including ecosystems and their services (*medium evidence*, *medium agreement*). Adaptation needs are the gap between what might happen as the climate changes and what we would desire to happen. The use of the term needs has also shifted with the framing of adaptation. In the National Adaptation Programmes of Action (NAPAs) "needs" were usually discussed in terms of major vulnerabilities and priority adaptation activities, and, in both developing and developed countries, this hazard-based approach with a focus on drivers of impacts and options to moderate them is still used often for urban or regional programs. But more recently, the focus has been on tackling the underlying causes of vulnerability such as informational, capacity, financial, institutional, and technological needs. {14.2}

Engineered and technological adaptation options are still the most common adaptive responses, although there is growing experience of the value for ecosystem-based, institutional, and social measures, including the provision of climate-linked safety nets for those who are most vulnerable (*robust evidence*, *high agreement*). Adaptation measures are increasing and becoming more integrated within wider policy frameworks. Integration, though it remains a challenge, streamlines the adaptation planning and decision-making process and embeds climate-sensitive thinking in existing and new institutions and organizations. This can help avoid mismatches with the objectives of development planning, facilitate the blending of multiple funding streams, and reduce the possibility of maladaptive actions. The increasing complexity of adaptation practice means that institutional learning is an important component of effective adaptation. {14.3}

Approaches to selecting adaptation options continue to emphasize incremental change to reduce impacts while achieving co-benefits, but there is increasing evidence that transformative changes may be necessary in order to prepare for climate impacts (*medium evidence*, *medium agreement*). While no-regret, low-regret, and win-win strategies have attracted the most attention in the past and continue to be applied, there is increasing recognition that an adequate adaptive response will mean acting in the face of continuing uncertainty about the extent of climate change and the nature of its impacts, and that in some cases there are limits to the effectiveness of incremental approaches. While attention to flexibility and safety margins is becoming more common in selecting adaptation options, many see the need for more transformative changes in our perception and paradigms about the nature of climate change, adaptation, and their relationship to other natural and human systems. {14.1, 14.3.4}

Among the many actors and roles associated with successful adaptation, the evidence increasingly suggests two to be critical to progress: those associated with local government and those with the private sector (*medium evidence*, *high agreement*). These two groups will bear increasing responsibility for translating the top-down flow of risk information and financing and in scaling up the bottom-up efforts of communities and households in planning and implementing their selected adaptation actions. Local institutions, including local governments, non-government organizations (NGOs), and civil society organizations, are among the key actors in adaptation but are often limited by lack of resources and capacity and by continuing difficulties in gaining national government or international support, especially in developing countries. {14.2.3} Private entities, from individual farmers and small to medium enterprises (SMEs) to large corporations, will seek to protect and enhance their production systems, supply lines, and markets by pursuing adaptation-related opportunities. These goals will help expand adaptation activities but they may not align with government or community objectives and priorities without coordination and incentives. {14.2.4}

Adaptation assessments, which have evolved in substance and style since AR4, have demonstrably led to a general awareness among decision makers and stakeholders of climate risks and adaptation needs and options. However, such awareness has often not translated into adaptation action (*medium evidence*, *high agreement*). Most of the assessments of adaptation done so far have been restricted to impacts, vulnerability, and adaptation planning, with very few assessing the processes of implementation and evaluation of actual adaptation actions. {14.4.1} Assessments that include both top-down assessments of biophysical climate changes and bottom-up assessments of what makes people and natural systems vulnerable to those changes will help to deliver local solutions to globally derived risks. Also, assessments that are linked more directly to particular decisions and that provide information tailored to facilitate the decision-making process appear to have most consistently led to effective adaptation measures. {14.4.3}

The evidence to support the most valuable metrics of adaptation needs and effectiveness is limited, but increasing (*medium evidence*, *high agreement*). {14.5.2-3} At present, there are conflicting views concerning the choice of metrics, as governments, institutions, communities, and individuals value needs and outcomes differently and many of those values cannot be captured in a comparable way by metrics. {14.5} The demand for metrics to measure adaptation needs and effectiveness is increasing as more resources are directed to adaptation. These indicators that are proving most useful for policy learning are those that track not just process and implementation, but also the extent to which targeted outcomes are occurring. {14.5.2.3}

Maladaptation is a cause of increasing concern to adaptation planners, where intervention in one location or sector could increase the vulnerability of another location or sector, or increase the vulnerability of the target group to future climate change (*medium evidence*, *high agreement*). {14.7.3} The definition of maladaptation used in AR5 has changed subtly to recognize that maladaptation arises not only from inadvertent badly planned adaptation actions, but also from deliberate decisions where wider considerations place greater emphasis on short-term outcomes ahead of longer-term threats, or that discount, or fail to consider, the full range of interactions arising from the planned actions. {14.6.1}

14.1. Introduction

This chapter establishes a foundation for understanding adaptation by reviewing core concepts related to adaptation, with a focus on mapping out broad categories of needs and options. Here we use adaptation needs to refer to circumstances requiring information, resources, and action to ensure safety of populations and security of assets in response to climate impacts. Adaptation options are the array of strategies and measures available and appropriate to address needs. Because identifying needs and selecting and implementing options require the engagement of individuals, organizations, and governments at all levels, this chapter also briefly considers the range of actors involved in these processes and summarizes the risks of maladaptation.

Other chapters in this report, namely Chapter 4 and in particular Section 4.4, and supported by Chapters 3, 5, 6, and 7, deal with the threats of climate change on ecosystems and other predominately natural systems and their prospects and options for adaptation. For the sake of space and clarity this chapter focuses on the socioeconomic systems that support human livelihoods, although it also touches on the services provided by ecosystems (including ecosystem-based adaptation).

This chapter also highlights some important tools for implementing adaptation, namely approaches to assessing needs at national, subnational, and sectoral levels, and the challenges of applying metrics to determine adaptation needs and the effectiveness of adaptation actions. In the course of these discussions, this chapter establishes a foundation for the three adaptation chapters that follow. The existence of adaptation options does not necessarily mean that these options can be implemented when the need arises. Therefore, Chapter 15 examines adaptation planning and implementation, including the challenges faced and how these can be addressed. Chapter 16 focuses on adaptation opportunities and constraints, while Chapter 17 assesses the economics of adaptation to climate change, including the costs and benefits of adaptation and of inaction. This chapter also draws on, and seeks not to repeat, the detailed discussions of human health, well-being, security, livelihoods, and poverty found in Chapters 11, 12, and 13 that are so important to the wider discussion of adaptation. These and other interactions among the adaptation chapters are illustrated in Figure 14-1.

Human and natural systems have a capacity to cope with adverse circumstances but, with continuing climate change, adaptation will be needed to maintain this capacity (IPCC, 2012; see also Section 1.4.1 and Box 2.1). The AR5 definition of adaptation (i.e., "The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects…") follows the lead of the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) in introducing a degree of purposefulness by adding the phrase "which seeks to moderate" rather than simply "which moderates" as in AR4.[1] Human ability to cope with climate impacts can also be increased by actions that are not anticipatory or purposefully undertaken in response to observed or anticipated climate change, sometimes called unplanned actions. For example, diversifying livelihoods in response to immediate economic factors can increase long-term ability to cope with a changing climate. Such actions were often referred to as autonomous adaptation. However, the use of the term in the literature, including the IPCC reports, has been inconsistent. The term is often used to refer to purposeful adaptation actions carried out by agents without external inputs such as policies, information, or resources (see Chapters 17, 22; Skoufias, 2012), and sometimes to refer to purposeful actions that are reactive to experienced climate impacts, rather than being proactive or anticipatory of them (see Glossary and WGII AR3 Section 18.2.3).

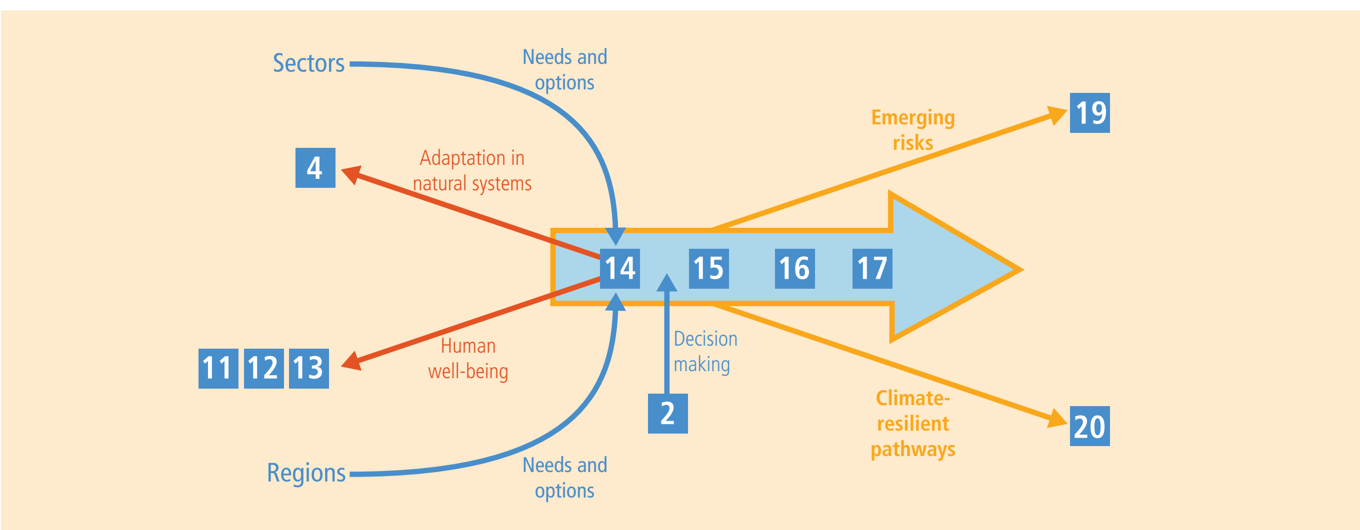

Figure 14-1 | The relationship between the four adaptation chapters (14 to 17) and other closely related chapters. Chapter 14 (Adaptation Needs and Options) draws on and cross-references many of the issues of human well-being, including health, security, and poverty; the treatment of adaptation of natural ecosystems is dealt with mainly in Chapter 4 and is not repeated in Chapter 14. Similarly the needs and options synthesized in Chapter 14 are drawn largely from the sectoral (3 to 10) and regional chapters (21 to 30). Chapter 2 provides input to decision-making approaches relevant to Chapter 15 (Adaptation Planning and Implementation). All the adaptation chapters feed into the synthesis of Chapters 19 (Emerging Risks and Key Vulnerabilities) and 20 (Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development).

The SREX and AR5 definitions of adaptation also clarify the distinction between adaptation in human and natural systems. Natural systems have the potential to adapt through multiple autonomous processes (e.g., phenology changes, migration, compositional changes, phenotypic acclimation, and/or genetic changes), and humans may intervene to promote particular adjustments such as reducing non-climate stresses or through managed migration (see Section 4.5). But successful adaptation will depend on our ability to allow and facilitate natural systems to adjust to a changing climate, thus maintaining the ecosystem services on which all life depends.

Adaptation is becoming increasingly important in climate negotiations and implementation, and integral to AR5 are the terms incremental and transformational adaptation—sometimes referred to as a "paradigm shift" as in the Green Climate Fund Governing Instrument (Green Climate Fund, 2013a). Incremental adaptation refers to actions where the central aim is to maintain the essence and integrity of the existing technological, institutional, governance, and value systems, such as through adjustments to cropping systems via new varieties, changing planting times, or using more efficient irrigation. In contrast, transformational adaptation seeks to change the fundamental attributes of systems in response to actual or expected climate and its effects, often at a scale and ambition greater than incremental activities. It includes changes in activities, such as changing livelihoods from cropping to livestock or by migrating to take up a livelihood elsewhere, and also changes in our perceptions and paradigms about the nature of climate change, adaptation, and their relationship to other natural and human systems (Sections 3.3, 8.6.2.3, 20.5 and FAQ 8.2; IPCC, 2012; Kates et al., 2012; Park et al., 2012; Green Climate Fund, 2013b). Transformational change may be driven by the pursuit of better opportunities or by the realization of the imminent or inevitable limits within existing paradigms (Dow et al., 2013; Section 16.4.2). Transformative change may threaten the status quo for many and require leadership and sometimes triggering events to initiate it (Kates et al., 2012). However, transformational change is not called for in all responses to climate change (Pelling, 2010) and ill-prepared transformative change may bring with it social inequities (O'Brien, 2012). The triggers for transformational change and its implementation are dealt with in more detail in Sections 16.4 and 20.5. Differentiation between incremental and transformative adaptation, although indistinct, is important because it affects how we approach adaptation, how we integrate it into planning and policy, and how we allocate adaptation funding in both developed and developing countries (IPCC, 2012; see also Chapter 17).

Another concept is the adaptation deficit, which is the gap between the current state of a system and a state that would minimize adverse impacts from existing climate conditions and variability (see Glossary); that is, it is essentially inadequate adaptation to the current climate conditions (Burton et al., 2002; Burton, 2004; Burton and May, 2004; Parry et al., 2009; see also Sections 17.2.2.2, 17.6.1). Some have suggested that it is often part of a larger "development deficit" (World Bank, 2010). Delay in action in both mitigation and adaptation will increase the adaptation deficit in many parts of the world (IPCC, 2012).

[1] Purposefulness was introduced in the SREX definition, which introduced the phrase "in order to moderate".

In the process of building future adaptive capacity it is important to reduce the current adaptation deficit along with designing effective risk management and climate change adaptation measures (Hallegatte, 2011). Failure to close the adaptation deficit, both current and in the future, will result in residual damages from climate change. There have been calls for such residual damages to be evaluated and reported (Parry et al., 2009).

Summary of Key Findings from AR4

In the Working Group II (WGII) Fourth Assessment Report (AR4), the main chapter on adaptation (Chapter 18) refined the basic terminology of adaptation and concluded that adaptation to climate change was already taking place, but on a limited basis. Societies have a long record of adapting to the impacts of weather and climate through a range of practices that include crop diversification, irrigation, water management, disaster risk management, and insurance, but climate change, along with other drivers of change, poses novel risks often outside the range of experience.

WGII AR4 found that deliberate adaptation measures in response to anticipated climate change were being implemented by a range of public and private actors, on a limited basis, in both developed and developing countries. These measures are undertaken through policies, investments in infrastructure and technologies, and behavioral change, and they are seldom undertaken in response to climate change alone. Many actions that facilitate adaptation to climate change are undertaken to deal with current extreme events, such as heat waves and cyclones, and are often embedded within broader sectoral initiatives such as water resource planning, coastal defense, and disaster management planning.

WGII AR4 concluded that there are individuals and groups within all societies that have insufficient capacity to adapt to climate change. The capacity to adapt is dynamic and influenced by economic and natural resources, social networks, entitlements, institutions and governance, human resources, and technology. However, high adaptive capacity does not necessarily translate into actions that reduce vulnerability. New planning processes are being implemented to attempt to overcome these barriers at local, regional, and national levels in both developing and developed countries. WGII AR4 noted the establishment of the National Adaptation Programmes of Action (NAPAs) and that some developed countries had established national adaptation policy frameworks. Other conclusions from the WGII AR4 relating to the implementation of adaptation policies and measures, barriers to adaptation, and the economic costs of adaptation are summarized in Chapters 15, 16, and 17 of this report.

14.2. Adaptation Needs

Adaptation involves reducing risk and vulnerability; seeking opportunities; and building the capacity of nations, regions, cities, the private sector, communities, individuals, and natural systems to cope with climate impacts, as well as mobilizing that capacity by implementing decisions and actions (Tompkins et al., 2010). Vulnerability is the "propensity or predisposition [of a system] to be adversely affected" (see Glossary) and, until AR4, was viewed as comprising three elements: exposure, sensitivity, and adaptive capacity (IPCC, 2007a). However, in IPCC (2012) and in this report, vulnerability focuses only on sensitivity and capacity, with exposure more appropriately incorporated into the concept of risk (see Glossary; IPCC, 2012, Section 2.2).

Adaptation requires adequate information on risks and vulnerabilities in order to identify needs and appropriate adaptation options to reduce risks and build capacity. In framing an approach to adaptation, it is important to engage people with different knowledge, experience, and backgrounds in tackling and reaching a shared approach to addressing the challenges (Preston and Stafford Smith, 2009; Tompkins et al., 2010; Fünfgeld and McEnvoy, 2011; Eakin et al., 2012) Initially, identifying needs was most often based on impact assessments (or risk-hazard approaches), but social vulnerability or resilience assessments are increasingly being used (Fünfgeld and McEnvoy, 2011; Preston et al., 2011b). The risk-hazard framework, drawn primarily from risk and disaster management, focuses on the adverse effects that natural hazards and other climate impacts can have on a given location (Füssel and Klein, 2006). The emphasis in this approach is on the physical and biological aspects of impacts and adaptation (Burton et al., 2002). The social vulnerability framework focuses on the reasons and ways in which individuals, groups, and communities are vulnerable to climate impacts. Here, the focus is on how different factors, such as institutions, shape the socioeconomic conditions that place human populations at risk (Adger and Kelly, 1999; Preston et al., 2011b). There are overlaps and complementarities between these frameworks. Approaches to identifying needs and options are discussed further in the section on assessments (Section 14.4).

Comprehensive assessments typically provide insight into the risks and vulnerabilities that will result from climate change in communities, cities, nations, and ecosystems and, in turn, offer a means to identify the presence of adaptation needs and options for addressing those needs. The term adaptation needs is often used but rarely defined in the adaptation literature. In the wider literature, a need can be seen as a problem that can be solved (McKillip, 1987) or as a gap between current outcomes and desired outcomes (Kaufman and English, 1979). Thus, in this context, adaptation needs are the gap between what might happen as the climate changes and what we would desire to happen. Also, the term adaptation needs is used in several ways in the adaptation literature. A common use is in the sense of the "urgent and immediate needs" relating to the adverse effects of climate change, as in the rationale for the NAPAs, although in this case "needs" were usually discussed in terms of major vulnerabilities and priority adaptation activities (by UNFCCC).[2] The most effective descriptions of these needs combined discussions of climate and non-climate drivers of impacts, and the resources, capacity, information, finance, etc., needed to implement options to moderate those impacts (e.g., GEF, 2002). Assessments of adaptation needs, both in developing and developed countries, have often taken a hazard-based approach with a focus on drivers of impacts and options to moderate them (Moser, 2009; Finzi Hart et al., 2012). But more recently, the focus has been on tackling the underlying causes of vulnerability (Füssel, 2007). One of the few categorizations of needs is that of Burton et al. (2006), who recognized information, capacity, financial, institutional, and technological needs. A similar structure is followed in this chapter. We first discuss biophysical and environmental needs on which all lives ultimately depend. Then we discuss social needs and capacities and how they vary throughout society. Third, we discuss our response to climate risks and impacts and how they are modified by the multitude of institutions through which humans work, ranging from international organizations to community-based efforts. Finally, we touch on resources, including societal needs for information and knowledge and financial resources.

Although needs are specific to particular groups and places, they fit into a set of more general categories as summarized in the sections below. For instance, vulnerability at the national and subnational levels is affected by geographic location, biophysical conditions, institutional and governance arrangements, and resource availability, including access to technology and economic stability (Brooks et al., 2005). At the macro-level, two broad classes of determinants of vulnerability are recognized: biophysical determinants and socioeconomic determinants (Preston et al., 2011a). However, adaptation needs are highly diverse and context specific, for instance, varying between islands even within nations such as the Solomon Islands (Section 29.6.1). Different stakeholder groups and individuals have differential adaptation needs and vulnerabilities. Adaptation needs are also dynamic, and future adaptation needs are highly dependent on the mitigation pathway that is taken. Furthermore, the constraints and limits to adaptation (see Chapter 16) are likely to mean that not all needs will be met, thereby emphasizing the need for monitoring to avoid crossing critical thresholds (Section 19.7.3).

14.2.1. Biophysical and Environmental Needs

Climate change is altering ecological systems, biodiversity, genetic resources, and the benefits derived with ecosystem services (Convention on Biological Diversity, 2009; Mooney et al., 2009; Hoegh-Guldberg, 2011). Climate change is inducing shifts in habitats that often cannot be followed by species (Section 4.3.4.1), leading to changed ecosystems, to local and global extinctions, and to the permanent loss of unique combinations of genes. For instance, González et al. (2010) used observed and modeled changes of global patterns of biome shifts under climate change to conclude that up to half of the terrestrial ecosystems were vulnerable as a result of changes from secondary stressors, such as wildfire and disease, and suggested significant changes to natural resource management plans. In addition to the responses of ecosystems to climatic change, a number of studies have identified impacts on ecosystem services, particularly the effects of climate change on agricultural productivity (Coles and Scott, 2009), freshwater ecosystems (Ormerod et al., 2010), and downstream industries and enterprises (Preston and Stafford Smith, 2009). Ecosystem services that are already under threat from the impacts of climate change include pollination, pest, and disease regulation (Section 4.3.4.4); climate regulation services; and potable water supply (Section 4.3.4.5). Further stressors will limit our options to respond to climate change (Section 14.3.2).

[2] https://unfccc.int/files/cooperation_support/least_developed_countries_portal/napa_project_database/application/pdf/napa_index_by_country.pdf.

Natural systems underpin human livelihoods, health, welfare, food security, and prosperity. Vital ecosystem services that need to be maintained include provisioning services such as food, fiber, and potable water supply; regulating services such as climate regulation, pollination, disease control, and flood control; and supporting services such as primary production and nutrient cycling (Section 4.3.4). Much of the water for human consumption originates on forested lands and the quality of the water is heavily dependent on the conditions of the ecosystems through which it flows. Ocean systems also provide climate regulation services, while coral reefs act as ecological buffers (Section 6.4.1.4). For instance, healthy coastal wetlands and coral reefs can help to protect against storm surges and rising sea levels (Hoegh-Guldberg, 2011), while the maintenance of wetlands and green spaces can control runoff and flooding associated with increases in precipitation (Jentsch and Beierkuhnlein, 2008; Mooney et al., 2009). Meanwhile, fisheries and aquaculture contribute more than 20% to the dietary animal protein of nearly 1.5 billion people (Section 5.4.3.3).

Consequently, there is a need to protect these systems and resources within the changing climate. Goldman et al. (2008) found that research projects focusing on delivering ecosystem services, rather than on biodiversity goals, attracted a wider set of funders and better encompassed the landscapes and the people within them. However, many practices to intervene to improve and maintain ecosystem services are based on limited experience and thus still untested assumptions and limited information (Carpenter et al., 2009). Hence, there is a need to improve understanding and valuation of ecosystem services provided by different adaptation options. There is also an urgent need for appropriate ecosystem monitoring to avoid crossing critical thresholds (see Section 19.7.4).

14.2.2. Social Needs

From a social perspective, vulnerability varies as a consequence of the capacity of groups and individuals to reduce and manage the impacts of climate change. Among the key factors determining vulnerability are gender, age, health, social status, ethnicity, and class (Smit et al., 2001; Adger et al., 2009a). For instance, the vulnerability to health-related impacts of climate change varies as a consequence of geographical location (Section 11.3.1), gender and age (Section 11.3.3), and socioeconomic status (Section 11.3.4). Poverty and persistent inequality may be the most salient of the conditions that shape climate-related vulnerability (Section 13.1.4). Climate change is expected to have a relatively greater impact on the poor as a consequence of their lack of financial resources, poor quality of shelter, reliance on local ecosystem services, exposure to the elements, and limited provision of basic services and their limited resources to recover from an increasing frequency of losses through climate events (Tol et al., 2004; Huq et al., 2007; Kovats and Akhtar, 2008; Patz et al., 2008; Revi, 2008; Allison et al., 2009; Shikanga et al., 2009; Gething et al., 2010; Moser and Satterthwaite, 2010; Rosenzweig et al., 2010; Skoufias et al., 2012). Owing to limited financial resources and often compromised health and nutritional status, the poor, along with the sick and elderly, are at increased risk from trauma, physical and mental illness, and death from climate impacts such as increased pollution, higher indoor temperatures, exposure to toxins and pathogens from floods, and the emergence of new disease vectors (Kasperson and Kasperson, 2001; Haines et al., 2006; Costello et al., 2009, 2011; O'Neill and Ebi, 2009; Tonnang et al., 2010; Ebi, 2011; Harlan and Ruddell, 2011; Huang et al., 2011; McMichael and Lindgren, 2011; Semenza et al., 2012). Climate change, climate variability, and extreme events can erode natural, physical, financial, human, and social and cultural assets (Section 13.2.1.1), and poverty traps arise when climate change, variability, and extreme events make the poor even poorer (Section 13.2.1.4).

Social needs under climate change include understanding emotional and psychological needs. In Australia, it has been found that extreme events such as floods, drought, and bushfire can lead to mental suffering, including post-traumatic stress disorder, resulting in the need for psychological support and counseling (The Climate Institute, 2011). For example, drought can increase suicide rates by 8% (Nicholls et al., 2006). Social psychological adaptation processes powerfully mediate public risk perceptions and understanding, psychological and social impacts, and coping responses, as well as behavioral adaptation (Reser and Swim, 2011). Yet little collaborative work or research has so far focused on the nature and dynamics of individual-level coping and adaptation processes and how they influence responses (Reser et al., 2012).

These individual factors also are often associated with and compounded by community-level conditions. Women often have unequal access to and control over resources, including land titles and water rights (UNDP, 2010; CGIAR, 2012; Verner 2012). Many poor and ethnic minorities live in substandard housing; lack access to basic services, savings, and insurance; have compromised health; and are at threat due to excessive densities, poor access roads, and inadequate access to safe water, sanitation, and drainage (Huq et al., 2007; Kovats and Akhtar, 2008; Revi, 2008; Shikanga et al., 2009; Moser and Satterthwaite, 2010). In rural areas, adaptation needs also are linked to the viability of agricultural activity (Bosello et al., 2009). Climate change will lead to higher prices and increased volatility in agricultural markets, which might undermine global food supply security (Section 9.3.3.3). Geographically, highly vulnerable regions are those exposed to sea level rise and extreme events, overlaid with high concentrations of multidimensional poverty (Section 13.2.2.1). There will be disproportionate impacts on developing countries that are dependent on climate-sensitive activities such as agriculture (Cline, 2007). However, middle-income populations can also be adversely impacted by climate change as a stressor adding to other effects.

The causes and solutions of vulnerability take place at different social, geographic, temporal, and political scales (Ribot, 2010). Therefore, to identify critical needs of populations, and the underlying conditions giving rise to these needs, some social assessments can benefit by looking across institutional domains and by spanning from the local to the national. Local assessments provide a means to identify existing vulnerabilities; the policies, plans, and natural hazards contributing to these vulnerabilities; as well as identifying adaptation actions. Social needs include the range of needs for human security (see Section 12.1.2), which include the universal and culturally specific, material, and non-material elements necessary to people to act on behalf of their interests. More specifically, at this level, social needs can be evaluated in terms of availability of natural, physical, human, political, and financial assets; stability of livelihood; and livelihood strategies (Moser, 2006; Heltberg et al., 2009). Alternatively, regional and national assessments can provide a basis for ascertaining institutional conditions associated with long-standing inequities and development paths that may need to be addressed in order to generate robust options.

Although different stakeholder groups have specific needs, an overarching adaptation need for communities, households, private sector, and institutions is the need for shared learning on adaptation. Adaptation has itself been referred to as a social learning process (Sections 15.6, 22.4.5.3). In particular, there is the need for human capacity and social capital to implement adaptation actions, including education and access to information (Brooks et al., 2005; Adger, 2006; Smit and Wandel, 2006). Improved information for adaptation can benefit from efforts to combine indigenous and scientific knowledge (Section 12.3).

14.2.3. Institutional Needs

Institutions, informal and formal, are enduring regularities of human action in situations structured by rules, norms, and shared strategies, as well as by the physical world (Crawford and Ostrom, 1995) and as such they provide the enabling environment for implementing adaptation actions (Bryan et al., 2009; Chuku, 2009; Aakre and Rübbelke, 2010; Compston, 2010; Moser and Ekstrom, 2011). These institutions provide the guides, incentives, or constraints that shape the distribution of climate risks, establish incentive structures that can promote adaptation, foster the development of adaptive capacity, and establish protocols for both making and acting on decisions (see Section 14.2.3.2; Chuku, 2009; Agrawal, 2010; Compston, 2010). In many instances, international and national-level policies and programs can facilitate localized strategies through the creation of legal frameworks and the allocation of resources (Adger, 2001; Bulkeley and Betsill, 2005; Corfee-Morlot et al., 2011). Overall, there is a need for effective institutions to identify, develop, and pursue climate-resilient pathways for sustainable development (Sections 20.2, 20.4.2), including strengthening the ability to develop new options through social, institutional, and technological innovation (Section 20.4.3). Chapter 15 further considers the institutional needs to mainstream adaptation into government planning.

Governments at all levels play important roles in advancing adaptation and in enhancing the adaptive capacity and resilience of diverse stakeholder groups. National governments are integral to advancing an adaptation agenda as they decide many of the funding priorities and tradeoffs, develop regulations, promote institutional structures, and provide policy direction to district, state, and local governments. In developing countries, national governments are usually the contact point and initial recipient of international adaptation financing. In some countries, both developed and developing, state governments lead the national government in promoting and implementing adaptation (Mertz et al., 2009). The engagement of national government actors can help mobilize political will, support the creation and maintenance of climate research institutions, establish horizontal networks that promote information sharing (Westerhoff et al., 2011), and, in some cases, facilitate the coordination of budgets and financing mechanisms (Alam et al., 2011; Kalame et al., 2011). Governments have the potential to directly reduce the risk and enhance the adaptive capacity of vulnerable areas and populations by developing and implementing locally appropriate regulations including those related to zoning, storm water management and building codes, and attending to the needs of vulnerable populations through measures such as basic service provision and the promotion of equitable policies and plans (Adger et al., 2003b; Brooks et al., 2005; Nelson et al., 2007; Agrawal and Perrin, 2008; Agrawal, 2010).

Among the important institutions in both developed and developing countries are those associated with local governments[3] as they have a major role in translating goals, policies, actions, and investments between higher levels of international and national government to the many institutions associated with local communities, civil society organizations, and non-government organizations (NGOs). SREX Chapter 5 (IPCC, 2012) extensively assesses the role and importance of the local scale institutions when adapting to extreme weather and climate events, highlighting that extreme weather and climate events are acutely experienced at local levels, and that local knowledge is important for managing impacts (Cutter et al., 2009). As institutional actors, local governments and community institutions influence the distribution of climate risks, mediate between levels of government as well as between social and political processes, and establish incentive structures that affect both individual and collective action at all levels (Agrawal and Perrin, 2008). They are in a pivotal position to promote widespread support for adaptation initiatives, foster intergovernmental coordination, and facilitate implementation, both directly and through mainstreaming into ongoing planning and work activities (Anguelovski and Carmin, 2011; Carmin et al., 2012).

There are a number of ongoing political issues that shape the relationships national and local governments have in managing climate risks (Corfee-Morlot et al., 2011). Governance failure has a significant influence on institutional vulnerability (see Section 19.6.1.3.3). For instance, short-term interests, when dealing with long-term issues, can limit incentives to make investments. Similarly, the proximity that authorities have to interest groups can sway their decisions toward other issues, while the drive to engage the public in planning and other activities can orient priorities in ways that do not support adaptation (Corfee-Morlot et al., 2011). Local governments also may lack institutional capacity or have difficulty gaining coordination among departments as conflicts emerge to obtain scarce resources (Satterthwaite and Dodman, 2009; Hardoy and Romero Lankao, 2011). In Bangladesh, the limited access of local governments to resources has been cited as a barrier to local adaptation (Christensen et al., 2012).

Tompkins et al. (2010) found from a survey of 300 projects identified as adaptive at local government level in the UK that more than half were driven by concerns not directly related to climate change. Nevertheless, there are a number of indicators that demonstrate whether local government has institutionalized and mainstreamed adaptation. These include the presence of an identifiable champion from within government, climate change being an explicit issue in municipal plans, resources

[3] Here local government is used to refer to second or third tiers or lower of government, below national and state or provincial government levels; it includes county, district, council, municipal, and similar levels of government.

dedicated to adaptation, and adaptation incorporated into local political and administrative decision making (Roberts, 2008, 2010).

Overall, it is important to match the appropriate institutional scale with the scale of implementation. For example, the Murray-Darling Basin in Australia includes significant water resources across four states requiring management institutions involving federal, state, and local governments to manage and allocate water use (Hussey and Dovers, 2006; see also Box 25-2). While governments have the potential to influence adaptive capacity, local governments often lack the human and technological capacity or mandate to develop and enforce regulations. Local governments, particularly those in developing countries, are faced with numerous challenges that limit their ability to identify needs and pursue adaptation options. Often, these governments must attend to backlogs of basic and critical services such as housing and water supply or focus their attention on addressing outmoded and outdated infrastructure. They also may lack institutional capacity or have difficulty gaining coordination among departments as conflicts emerge to obtain scarce resources (Hardoy and Romero Lankao, 2011, Villamizar, 2011). Adaptation will require an approach that devolves relevant decision making to the levels where the knowledge and capacity for effective adaptations reside (see Box 25-5). Sowers et al. (2011) maintain that, in the Middle East and North Africa, the largely centralized systems of planning, taxation, and revenue distribution lead to a focus on supply-side issues with little consideration of changing climates and demand management, which renders their populations vulnerable to climate-induced impacts on water resources due to weak integration with local constituencies.

There are critical institutional design issues that can be evaluated in order to understand institutional needs (Agrawal, 2010; Gupta et al., 2010). The first is the extent to which institutions are flexible to handle uncertainty. This includes flexibility across and within institutions to evaluate and reorganize delivery where necessary. The uncertainty associated with climate change, presence of rapidly changing information and conditions, and emerging ideas on how best to foster adaptation requires continual evaluation, learning, and refinement (Agrawal, 2010; Gupta et al., 2010). Second is the extent to which adaptation is or has the potential to be integrated into short- and long-term policy making, planning, and program development (Conway and Schipper, 2011). Third is the potential for effective coordination, communication, and cooperation within and across levels of government and sectors (Schipper, 2009; Agrawal, 2010; Conway and Schipper, 2011). Finally, to promote adaptive capacity, it is important to identify the extent to which institutions are robust enough to attend to the needs of diverse stakeholders and foster their engagement in adaptation decisions and actions (Urwin and Jordan, 2008; Gupta et al., 2010).

14.2.4. Need for Engagement of the Private Sector

The role of the private sector is important in delivering adaptation. Often, the focus falls on the role of the private financial sector in providing risk management options including insurance and finance for large projects (see Sections 15.4.4, 17.5.1). However, the delivery of adaptation actions ranges more widely and spans different types of private enterprise, from small farmers, to small to medium enterprises (SMEs), to multinational companies. KPMG International (2008) used published reports and interviews to identify the sectors where businesses considered they face the greatest climate-related risks. In order of perceived importance, the core risks were regulatory, physical, reputational, and litigation risks. The sectors identified as most at risk included an expected cluster around oil and gas and aviation, and also a group less commonly perceived to be at risk, including health care, the financial sector, tourism, and transport.

Khattri et al. (2010) have described three general ways in which the private sector can become involved in adaptation. The first, internal risk management, is critical to firms and enterprises protecting their own interests and ensuring continuity of supply and markets. The second form of involvement recognizes that business is a stakeholder and therefore needs to participate in public sector and civil society initiatives, such as The New York City Panel on Climate Change, which consists of diverse stakeholders, including representatives from the private sector (Rosenzweig et al., 2011). Third, climate adaptation also provides a wide range of new opportunities to the business community. Even in developing countries, where regulations and markets are often underdeveloped and business risks are high, Khattri et al., (2010) identified opportunities for working in the health care, waste and water management, sanitation, housing, energy, and information sectors through fostering cooperation across government departments and NGOs and promoting public-private partnerships.

Despite broad-scale recognition of the need to adapt, such as the World Economic Forum's (2012) ranking of the failure to adapt as one of the highest global risks and on a par with terrorism, and despite some examples of private sector engagement in adaptation, most assessments conclude that action in each of the potential arenas has been slow to emerge and that sharing of knowledge and experience has been limited (Khattri et al., 2010; Agrawala et al., 2011). KPMG International (2008) concluded that, while companies are well used to managing business risk, they have yet to integrate the long-term risks of climate change into these systems. Nor are they preparing to grasp the competitive advantages that will accrue to those taking early action. Most of the businesses interviewed appeared to be unsure of the scale of the threat and opportunities for their businesses or are awaiting further guidance and action by governments. They have trouble in accessing and applying information on the extent of the threats and impacts from climate change and have yet to engage in the detailed cost-benefit analysis of adaptive actions or inaction. The European Commission (2009), using case studies of both the public and private sectors, in eight countries, came to similar conclusions. A survey by West and Brereton (2013) of Australian businesses also concluded that most were only vaguely aware of the breadth of adaptation actions that may be required and concerned about information sharing and disclosure. The authors suggest a framework for disclosures of relevant business activities to both improve practice and cater for the needs of company boards, investors, and stakeholders. A survey commissioned by the Carbon Disclosure Project (Gardiner et al., 2007) found that among Standard and Poor's (S&P) 500 companies many more (about two-thirds of respondents) were prepared to report and share information on managing climate risks and adaptation plans than they were on mitigation.

Also, there are still questions of whether and how adaptation finance should be made available to the private sector in developing countries and under what circumstances (Persson et al., 2009; IFC, 2010; Agrawala et al., 2011), although this is being piloted through the Pilot Program for Climate Resilience (World Bank, 2008; IFC, 2010). Private sector engagement and investment in adaptation is expected to make a substantial contribution to reducing climate risk, but the distribution of its investments will be selective and will be unlikely to match government and civil priorities (Atteridge, 2011).

14.2.5. Information, Capacity, and Resource Needs

Successful implementation of adaptation actions depends on the availability of information, access to technology and funding (Yohe and Tol, 2001; Adger, 2006; Eakin and Lemos, 2006; Smit and Wandel, 2006; World Bank, 2010). In some cases a supposed lack of relevant and legitimate information has been used as a rationale for inaction (Moser and Ekstrom, 2011). To address this concern, the Nairobi Work Program—established at COP-12 in 2006, with a goal of helping developing countries make better informed decisions based on sound scientific, technical, and socioeconomic data—has included repeated calls for better observation systems, information sharing, and modeling capacity (UNFCCC/SBSTA/2008/3). Developed and developing countries have acted on this priority by establishing institutions to provide information services at national, regional, and global scales (CCCCC, 2011; UKCIP, 2011; NCCARF, 2012), and there is an ongoing need to promote information acquisition and dissemination (OECD, 2009). For example, information-related adaptation needs in Africa include additional vulnerability and impact assessments with greater continuity, country-specific socioeconomic scenarios, and greater knowledge on costs and benefits of different adaptation measures (Section 22.4.2). Research and development, knowledge, and technology transfer are also important for promoting adaptive capacity. However, providing information does not mean that users will be able to make effective use of it, and this information will often have to be tailored or translated to the individual context (Webb and Beh, 2013). Efficacy of scientific knowledge can be improved by calibration with indigenous knowledge (Section 20.4.2). There are also opportunities for technology transfer and innovation to be enhanced through information technologies (Section 20.4.3).

Financial resources for adaptation have been slower to become available for adaptation than for mitigation in both developed and developing countries (see Chapter 17). Adaptation finance made up probably only a fifth of initial allocations of fast-start funding (Ciplet et al., 2012); and much of this funding has been directed toward capacity-building, standalone projects, or pilot programs. This not only has left financial needs, but has also meant that there is less expertise in adaptation assessment and implementation, which is further confounded by the complex relationship between adaptation and more common sustainable development and/or poverty reduction planning (McGray et al., 2007). Adaptation cost estimates have been used to estimate the financial needs for adaptation, and these may well have been underestimated (see Section 17.4).

Overall, at both international and national levels there is a need to develop financial instruments that are equitable in both their delivery of resources and in sharing the burden of supporting the instruments (Levina, 2007; World Bank, 2010; see also Chapters 16, 17). In this regard, the Green Climate Fund (GCF) was established in 2010, based on the commitment by developed country parties to mobilize jointly US$100 billion per year by 2020 to address the needs of developing countries (UNFCCC, 2007). Deliberation over how adaptation finance needs will be met has become central to the UNFCCC policy agenda (Section 16.3.4). Also, financial mechanisms for disaster risk management are also inextricably linked with those for adaptation (Mechler et al., 2010). Lessons from recent recovery operations have emphasized the need for disaster preparedness along with longer term goals directed to building resilience, including maximizing the employment-creation benefits of adaptation measures (Harsdorff et al., 2011.)

Finances required in the future for climate change are estimated to approach levels on the order of current development expenditure, and there is a large gap in funding available for climate change responses in developing countries (Peskett et al., 2009). Therefore, there is a related need to design delivery channels so that funding benefits the poor, as they often are most vulnerable to the impacts of climate change and climate-related disasters. As well as channeling adaptation finance to governments, there is a need for finance to reach the most vulnerable people and for approaches to enable stakeholder participation (Section 15.2.3). For example, for adaptation financing, working at the subnational level will be important and mechanisms such as microfinance may be effective (Agrawala and Carraro, 2010). Another important concern is that, with new money being made available for climate change research, policy development, and practice, people may place too much emphasis on addressing climate change as an isolated priority to the detriment of other equally pressing social, economic, and environmental issues (Ziervogel and Taylor, 2008). For example, in small islands, there are concerns that placing adaptation above the critical development needs of the present could inadvertently reduce resilience (see Section 29.6).

14.3. Adaptation Options

Identifying needs stemming from climate risks and vulnerabilities provides a foundation for selecting adaptation options. Over the years, a number of categories of options have been identified. These options include a wide range of actions that, as summarized in Table 14-1, are organized into three general categories: structural/physical, social, and institutional.

There are many different ways that the range of adaptation options available could be categorized (Burton, 1996), thus any categorization is unlikely to be universally agreed on; but this aims to take into account the diversity of adaptation options for different sectors and stakeholders. Some options cut across several categories. National, sectoral, or local adaptation plans are likely to include a number of measures that are implemented jointly from across various categories including structural, institutional, and social options. Furthermore, some adaptation options are interrelated. For instance, institutions and information are prerequisites for effective early warning systems.

Adaptation constraints and limits mean not all adaptation needs will be met, and not all adaptation options will be possible (see Chapter 16,

Table 14-1 | Categories and examples of adaptation options.

Category		Examples of options*
Structural/ physical	Engineered and built environment	Sea walls and coastal protection structures (5.5.2 and 24.4.3.5; Figure 5-5); flood levees and culverts (26.3.3); water storage and pump storage (Section 23.3.4); sewage works (3.5.2.3); improved drainage (24.4.5.5); beach nourishment (5.4.2.1); flood and cyclone shelters (11.7); building codes (Section 8.1.5); storm and waste water management (8.2.4.1); transport and road infrastructure adaptation (8.3.3.6); floating houses (8.3.3.4); adjusting power plants and electricity grids (10.2.2; Table 10-2)
	Technological	New crop and animal varieties (7.5.1.1.1, 7.5.1.1.3, 7.5.1.3; Box 9-3; Table 9-7); genetic techniques (27.3.4.2); traditional technologies and methods (7.5.2, 27.3.4.2, 28.2.6.1, and 29.6.2.1); efficient irrigation (10.3.6 and 22.4.5.7; Box 20-4); water saving technologies (24.4.1.5 and 26.3.3) including rainwater harvesting (8.3.3.4); conservation agriculture (9.4.3.1 and 22.4.5.7); food storage and preservation facilities (22.4.5.7); hazard mapping and monitoring technology (15.3.2.3 and 28.4.1); early warning systems (7.5.1.1, 8.1.4.2, 8.3.3.3, 11.7.3, 15.4.3.2, 18.6.4, 22.2.2.1, 22.3.5.3, and 22.4.5.2); building insulation (8.3.3.3); mechanical and passive cooling (8.3.3.3); renewable energy technologies (29.7.2); second-generation biofuels (27.3.6.2)
	Ecosystem-based[a]	Cross Chapter Box CC-EA, Ecological restoration (5.5.2, 5.5.7, 9.4.3.3, and 27.3.2.2; Box 15-1) including wetland and floodplain conservation and restoration; increasing biological diversity (26.4.3); afforestation and reforestation (Box 22-2); conservation and replanting mangrove forest (15.3.4 and 29.7.2); bushfire reduction and prescribed fire (Section 24.4.2.5; Box 26-2); green infrastructure (e.g., shade trees, green roofs) (8.2.4.5, 8.3.3, 11.7.4, and 23.7.4); controlling overfishing (28.2.5.1 and 30.6.1); fisheries co-management (9.4.3.4 and 27.3.3.1); assisted migration or managed translocation (4.4.2.4, 24.4.2.5, 24.4.3.5, and 25.6.2.3); ecological corridors (4.4.2.4); ex situ conservation and seed banks (4.4.2.5); community-based natural resource management (CBNRM) (22.4.5.6); adaptive land use management (Section 23.6.2)
	Services	Social safety nets and social protection (Box 13-2; 8.3, 17.5.1, and 22.4.5.2); food banks and distribution of food surplus (29.6.2.1); municipal services including water and sanitation (3.5.2.3 and 8.3.3.4); vaccination programs (11.7.1), essential public health services (11.7.2) including reproductive health services (11.9.2) and enhanced emergency medical services (8.3.3.8); international trade (9.3, 9.4, and 23.9.2)
Social	Educational	Awareness raising and integrating into education (11.7, 15.2, and 22.4.5.5); gender equity in education (Box 9-2); extension services (9.4.4); sharing local and traditional knowledge (12.3.4 and 28.4.1) including integrating into adaptation planning (29.6.2.1); participatory action research and social learning (22.4.5.3); community surveys (Section 8.4.2.2); knowledge-sharing and learning platforms (8.3.2.2, 8.4.2.4, 15.2.4.2, and 22.4.5.4); international conferences and research networks (8.4.2.5); communication through media (22.4.5.5)
	Informational	Hazard and vulnerability mapping (11.7.2, 8.4.1.5); early warning and response systems (15.4.2.3 and 22.4.5.2) including health early warning systems (11.7.3, 23.5.1, 24.4.6.5, and 26.6.3); systematic monitoring and remote sensing (15.4.2.1 and 28.6); climate services (2.3.3) including improved forecasts (27.3.4.2); downscaling climate scenarios (8.4.1.5); longitudinal data sets (26.6.2); integrating indigenous climate observations (22.4.5.4, 25.8.2.1, and 28.2.6.1); community-based adaptation plans (5.5.1.4 and 24.4.6.5) including community-driven slum upgrading (8.3.2.2) and participatory scenario development (22.4.4.5)
	Behavioral	Accommodation (5.5.2); household preparation and evacuation planning (23.7.3); retreat (5.5.2) and migration (29.6.2.4), which has its own implications for human health (11.7.4) and human security (12.4.2); soil and water conservation (23.6.2 and 27.3.4.2); livelihood diversification (7.5.1.1, 7.5.2, and 22.4.5.2); changing livestock and aquaculture practices (7.5.1.1); crop-switching (22.3.4.1); changing cropping practices, patterns, and planting dates (7.5.1.1.1, 23.4.1, 26.5.4, and 27.3.4.2; Table 24-2); silvicultural options (25.7.1.2); reliance on social networks (Section 29.6.2.2)
Institutional	Economic	Financial incentives including taxes and subsidies (Box 8-4; 8.4.3 and 17.5.6); insurance (8.4.2.3, 13.3.2.2, 15.2.4.6, 17.5.1, 26.7.4.3, and 29.6.2.2; Box 25-7) including index-based weather insurance schemes (9.4.2 and 22.4.5.2); catastrophe bonds (8.4.2.3 and 10.7.5.1); revolving funds (8.4.3.1); payments for ecosystem services (9.4.3.3 and 27.6.2; Table 27-7); water tariffs (8.3.3.4.1 and 17.5.3); savings groups (8.4.2.3 and 11.7.4; Box 9-4); microfinance (Box 8-3; 22.4.5.2); disaster contingency funds (22.4.5.2 and 26.7.4.3); cash transfers (Box 13-2)
	Laws and regulations	Land zoning laws (22.4.4.2 and 23.7.4); building standards (8.3.2.2, 10.7.5, and 22.4.5.7); easements (27.3.3.2); water regulations and agreements (26.3.4 and 27.3.1.2); laws to support disaster risk reduction (8.3.2.2); laws to encourage insurance purchasing (10.7.6.2); defining property rights and land tenure security (22.4.6 and 24.4.6.5); protected areas (4.4.2.2); marine protected areas (Box CC-CR Chapter 6; 23.6.5 and 27.3.3.2); fishing quotas (23.9.2); patent pools and technology transfer (15.4.3 and 17.5.5)
	Government policies and programs	National and regional adaptation plans (15.2 and 22.4.4.2; Box 23-3) including mainstreaming climate change; sub-national and local adaptation plans (15.2.1.3 and 22.4.4.4; Box 23-3); urban upgrading programs (8.3.2.2); municipal water management programs (8.3.3.4; Box 25-2); disaster planning and preparedness (11.7); city-level plans (8.3.3.3 and 27.3.5.2; Boxes 26-3 and 27-1), district-level plans (26.3.3), sector plans (26.5.4), which may include integrated water resource management (3.6.1 and 23.7.2), landscape and watershed management (4.4.2.3), integrated coastal zone management (2.4.3, 5.5.4.1, and 23.7.1), adaptive management (2.2.1.3 and 5.5.1.4; Box 5-2), ecosystem-based management (6.4.2.1), sustainable forest management (2.3.4), fisheries management (7.5.1.1.3 and 30.6.2.1), and community-based adaptation (5.5.4.1, 8.4, 15.2.2, 21.3.2, 22.4.4.5, 24.5.2, 29.6.2.2, and 29.6.2.3; Tables 5-4 and 8-4; FAQ 15.1)

Notes: These adaptation options should be considered overlapping rather than discrete, and are often pursued simultaneously as part of adaptation plans. Examples given can be relevant to more than one category.

[a]A number of these would fall under the term "green infrastructure" in some European Commission documents (European Commission, 2009).
*WGII AR5 sections containing representative sample of adaptation options.

particularly Section 16.7.1). Moreover, adaptation options are not available to meet all adaptation needs. For instance, adaptation options are poorly developed for the broader set of impacts on ocean systems (see Section 30.6). There is also often going to be a gap between adaptation needs and the effectiveness of the options to meet these needs even when well resourced and well implemented. Some of this gap may be met by procedures to deal with loss and damage (Section 19.7) and some adaptation deficit will remain with us. Many of the adaptation options intersect with vulnerability reduction and development options that build adaptive capacity and address the "adaptation deficit" which may be seen as part of a wider "development deficit" (McGray et al., 2007; see also Section 2.4.2).

14.3.1. Structural and Physical Options

This category highlights adaptation options that are discrete, with clear outputs and outcomes that are well defined in scope, space, and time. They include structural and engineering options; the application of discrete technologies; the use of ecosystems and their services to serve adaptation needs; and the delivery of specific services at the national, regional, and local levels. This category includes much of the notion of "concrete activities" that reflect the priority of the Adaptation Fund, where the focus is on "discrete activities with a collective objective(s) and concrete outcomes and outputs that are more narrowly defined in scope, space, and time" (Adaptation Fund Board, 2013).

14.3.1.1. Engineering and Built Environment

Engineering, and the multidisciplinary teams engineers work with (architects, planners, legal experts, etc.), is often at the forefront of delivering adaptation technologies and strategies (Dawson, 2007). Most engineering options are expert driven, capital-intensive, large-scale, and highly complex (McEvoy et al., 2006; Morecroft and Cowan, 2010; Sovacool, 2011). While many of the engineering options—including management of storm and waste water flow (both inland and coastal), flood levees, seawalls, upgrading existing infrastructures to improve wind and flooding resilience, beach nourishment, and retrofitting buildings (Blanco et al., 2009; Koetse and Rietveld, 2012; Ranger and Garbett-Shiels, 2012)—are extensions and improvements of existing practices, plans, and structures; some newer projects are now integrating changed climate risk into the initial design. For example, during the engineering design of the Qinghai-Tibet Railway, various measures were proposed to ensure the stability of the railway embankment in permafrost regions (Wu et al., 2008). Section 5.5.4.1 describes how new coastal protection structures in Japan are being upgraded to take into account future sea level rise.

Engineered adaptation options typically have two general limitations. First, they often must cope with uncertainties associated with projecting climate impacts arising from assumptions about future weather, population growth, and human behavior (Dawson, 2007; Furlow et al., 2011). Second, the longevity and cost of engineered infrastructure affect the feasibility at the outset (Koetse and Rietveld, 2012). They also are subject to consequences that were not anticipated. For example, after coastal eastern England was devastated by the North Sea storm surge in 1953, hard-engineered sea walls were put in place to protect the coast from erosion and inundation. However, the engineered alterations resulted in a new array of coastal instabilities, including disturbances in sediment supply and damages to coastal ecosystems (Adger et al., 2009b; Turner et al., 2010). As a result, many have promoted a "phased capacity expansion" strategy, which allows engineered projects to undertake design modification as conditions or knowledge change and facilitate incremental project construction to ease the burden of upfront financing (Colombo and Byer, 2012). An example is the Thames Estuary 2100 Plan (see Box 5-1) and, in the Netherlands, the Delta Works (Arnold et al., 2011).

14.3.1.2. Technological Options

Recent advances in technology and information are being combined with engineering structural adaptation measures in various applications. In the food and agriculture sector, a suite of adaptation options have been developed and applied to reduce the adverse impacts of climate change on production (FAO, 2007; Stokes and Howden, 2010; see also Chapters 7, 9). Technologies range from more efficient irrigation and fertilization methods, plant breeding for greater drought tolerance, and adjusting planting based on projected yields (Semenov, 2006, 2008; Bannayan and Hoogenboom, 2008) to transfers of traditional technologies such as floating gardens (Irfanullah et al., 2011a,b). Technology options for climate change adaptation include both "hard" and "soft" technologies, and not only new technologies but also indigenous and locally made appropriate technology (Glatzel et al., 2012). For example, traditional construction methods have been identified across the Pacific as a means of adapting to tropical cyclones and floods, including building low aerodynamic houses and the use of traditional roofing material such as sago palm leaves to reduce the hazard of iron roofing being blown away in high winds (see Section 29.6.2.1). Centralized high-technology systems can increase efficiency under normal conditions, but also risk cascading malfunctions in emergencies (Section 15.4.3).

With the rapid diffusion of Information and Communication Technologies (ICT) such as mobile phones and the Internet, the unprecedented speed at which information is produced and shared is posing a new set of possibilities for communication. ICT provides opportunities for top-down dissemination of relevant information such as weather forecasts, hazard warnings, market information, information sharing, and advisory services. It can also generate essential information through bottom-up processes such as "crowd sourcing" of useful information such as local flood levels, disease outbreaks, and the management of disaster responses. MacLean (2008) identifies three kinds of effects of the rapid advances in ICT on adaptation and development in general: direct use for monitoring and measuring climate change as described earlier, as a medium for raising awareness, and as an enabler for a "networked governance" based on networked open organizations. Pant and Heeks (2011) emphasize the difficulty in foreseeing additional applications arising from planned ICT applications exploiting local creativity and entrepreneurship, but warn that ICT itself is not a panacea and that the most effective applications are embedded in other societal behaviors.

There are repeated calls for technology transfer to and sharing between developing countries in adaptation to match the programs associated with mitigation (UNFCCC, 2006). Unlike mitigation, where low-carbon technologies are often new and protected by patents held in developed countries, in adaptation the technologies are often familiar and applied elsewhere. For example, agricultural practices that are well known in a region some distance away may now be applicable but unfamiliar within a region of interest (Irfanullah et al., 2011a). Thus, technology transfer in adaptation may be easier than for mitigation. For example, to address water scarcity issues in many places, water storage, use, and water efficiency technologies will all need to be more widely available. See also Section 15.3.4 on technology transfer and diffusion.

14.3.1.3. Ecosystem-Based Adaptation

Ecosystem-based adaptation (EBA)—which is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (Convention on Biological Diversity, 2009)—is becoming an integral approach to adaptation (see Box CC-EA). Often, when faced with climate-related threats, first consideration is given to engineered and technological approaches to adaptation. However, working with nature's capacity and pursing ecological options, such as coastal and wetland maintenance and restoration, to absorb or control the impact of climate change in urban and rural areas can be efficient and effective means of adapting (Huntjens et al., 2010; Jones et al., 2012). The use of mangroves and salt marshes as a buffer against damage to coastal communities and infrastructure has been well researched and found to be effective both physically and financially in appropriate locations (Day et al., 2007;

Morris, 2007). They can also provide biodiversity co-benefits, support fish nurseries, and have carbon sequestration value (Adger et al., 2005; Reid and Huq, 2005; Convention on Biological Diversity, 2009). Other EBA activities include integrative adaptive forest management (Bolte et al., 2009; Guariguata, 2009; Reyer et al., 2009), and the use of agro-ecosystems in farming systems (Tengö and Belfrage, 2004), ecotourism activities (Adler et al., 2013), land and water protection and management, and direct species management (Mawdsley et al., 2009). An analysis of the 44 submitted NAPAs showed that the value of ecosystem services was acknowledged in 50% of the national proposals and, in 22% of the proposals, included the use of ecosystem services mostly in support of other adaptation activities including infrastructure, soil conservation, and water regulation (Pramova et al., 2012).

Green infrastructure (including the use of green roofs, porous pavements, and urban parks) can improve storm water management and reduce flood risk in cities, and can moderate the heat-island effect, as well as having co-benefits for mitigation (Section 8.3.3.7). For example, New York City has a well-established program to enhance its water supply through watershed protection that is cost-effective compared to constructing a filtration plant (Section 8.3.3.7). However, there are trade-offs relating to land use and the availability of space for people and social, economic, and environmental activities. For example, providing an effective wetland buffer for coastal protection may require emphasis on silt accumulation possibly at the expense of wildlife values and recreation (Convention on Biological Diversity, 2009; Dudley et al., 2010). Similarly Goldstein et al. (2012) found that in land use decision making in Hawaii trade-offs existed between carbon storage and water quality, and between environmental improvement and financial returns. A further consideration is that ecosystem-based approaches are often more difficult to implement and assess as they usually require cooperation across institutions, sectors, and communities, and their benefits are also spread across a similarly wide set of stakeholders (Jones et al., 2012). One of the major barriers to EBA is the lack of comparable standards and methodologies applied to engineering approaches, thus demonstrating the need for more dialog between engineering and ecological communities.

14.3.1.4. Service Options

Service provision consists of a diverse range of specific and measurable activities. For instance, one measure to support the most vulnerable populations is social safety nets. Efforts to address child malnutrition, which often result from loss of livelihood due to extreme weather events, particularly floods and droughts (Hoddinott et al., 2008; Alderman et al., 2009), offer an example of how safety nets can serve as a climate adaptation measure. While some studies have shown that food programs can be counterproductive to promoting livelihoods over the longer term or may not prevent malnutrition in non-emergency situations (e.g., Bhutta et al., 2008), programs designed to provide support via food programs, micro-finance, or insurance at times of extreme events can provide an important bridge for vulnerable populations (Hoeppe and Gurenko, 2006; Hochrainer et al., 2007; Alderman et al., 2009; Meze-Hausken et al., 2009).

Public health services also are important for tackling projected increases of disease incidences spurred on by climate change (Ebi and Burton, 2008; Garg et al., 2009; Edwards et al., 2011; Huang et al., 2011). For example, in countries where malaria is endemic, frequent adaptation options for addressing possible outbreaks include increasing use of mosquito nets, insecticides sprays, and controlling mosquito breeding by reclaiming land and filling drains (Garg et al., 2009). Governments at all levels are often also responsible for maintaining adequate access to services that are projected to be further stressed due to climate change (Laukkonen et al., 2009). Frequently cited options in this domain include, among others, clearing drainage systems to prevent floods, diversifying water supply services to account for changing water supplies (Kiparsky et al., 2012), and maintaining open public spaces dedicated for disaster recovery and other emergency purposes (Hamin and Gurran, 2009).

At the local level, infrastructure associated with the provision of basic services, such as water, sanitation, solid waste disposal, power, storm water and roadway management, and public transportation are integral to increasing adaptive capacity (Paavola, 2008; Bambrick et al., 2011; Barron et al., 2012; see also Section 8.2.4.1). Transport links enable households to take part in trade, for example, to access agricultural markets (Section 9.3.3.3.2) although supply chains can be vulnerable to climate disruption. Housing services are particularly critical because new patterns in temperature and precipitation will alter the habitability and stability of residences while increased frequency and intensity of natural disasters will place settlements and homes on both stable and unstable land at greater risk (Satterthwaite and Dodman, 2009; see also Section 8.3.3.3). Although one option is to relocate people inhabiting vulnerable areas, some argue that *in situ* upgrading may be more cost-effective, especially for addressing informal settlements in developing countries (Revi, 2008).

14.3.2. Social Options

There are various adaptation options that target the specific vulnerability of disadvantaged groups, including targeting vulnerability reduction and social inequities. Community-based adaptation (CBA) refers to the generation and implementation of locally driven adaptation strategies, operating on a learning-by-doing, bottom-up, empowerment paradigm that cuts across sectors and technological, social, and institutional processes. Social protection schemes (see also Section 14.3.1 on services) include public and private initiatives that transfer income or assets to the poor, protect against livelihood risks, and raise the social status and rights of those who are marginalized (see Box 13-2). An example of a social protection scheme aimed at moving beyond repeated relief interventions is Ethiopia's Productive Safety Net Program (PSNP) (Section 22.4.5.2).

The complexity of climate adaptation means that adaptation options are heavily influenced by forms of learning and knowledge sharing (Collins and Ison, 2009). Many scholars have noted that education is a key indicator for how people select adaptation options (Chinowsky et al., 2011; Sovacool et al., 2012), while a lack of education is a constraint that contributes to vulnerability (Paavola, 2008). For example, in a study of how farmers in the Nile Basin of Ethiopia select adaptation options, the researchers found a positive relationship between the education level of the household head and the adoption of improved technologies and adaptation to climate change (Deressa et al., 2009a,b). In Bangladesh, education about disaster responses was greatly assisted by rising literacy rates, especially among women (Section 11.7).

Awareness raising, extension, outreach, community meetings, and other educational programs are important for disseminating knowledge about adaptation options (Aakre and Rübbelke, 2010; Birkmann and Teichman, 2010) as well as for helping to build social capital that is critical for social resilience (Adger, 2003; Krasny et al., 2010; Wolf et al., 2010). In this regard, education can be seen as a public good that promotes dialog and networks (Boyd and Osbahr, 2010), and therefore allows the development of resilience at both the level of the individual learner and at the level of socio-ecological systems (Krasny et al., 2010). Research partnerships and networks can facilitate knowledge-sharing and awareness raising at all levels from small groups of individuals to large institutions (Section 8.4.2.5). Communication and dialog on adaptation can be a two-way flow of information. Adaptation has itself been described as a social learning process (Section 15.3.1.2), and a number of initiatives in Africa emphasized the importance of iterative and experiential learning for flexible adaptation planning (Suarez et al., 2009; see also Section 22.4.5.3). In Maryland a half-day role-playing process has been designed to both help local people, working with key local and state experts and planners, to plan and prepare for sea level rise and other coastal impacts. It allows them to experience first hand the diversity of stakeholders, the conflicting decisions to be made, and the need to communicate throughout their community to adapt to new risks (Anon, 2009). A similar role-playing game has been developed for the Chesapeake Bay of the eastern United States (Learmonth et al., 2011).

Informational strategies are integral to adaptation. Early warning systems are critical to ensuring awareness of natural hazards and to promoting timely response, including evacuation. A number of approaches are being employed around the world, including tone alert radio, emergency alert system, presentations, and briefings (Van Aalst et al., 2008; Ferrara de Giner et al., 2012). Heat wave and health warning systems (HHWS) can be designed to prevent negative health impacts, by predicting possible health outcomes, identifying triggers, and communicating prevention responses (Section 11.7.3).

Climate services initially emerged as an expansion of the tasks provided by weather services, and can act as "knowledge brokers" that establish a dialog between science and the public, to facilitate decision support (Section 2.4.1.2). Linking indigenous and conventional climate observations can add value, for example, in western Kenya, where scientists have worked with local rainmakers to develop consensus forecasts (Section 22.4.5.4). Awareness raising through scenario development, computer modeling, and role playing is effective in preparing both responsible authorities and the public. As previously noted, ICT is facilitating rapid dissemination of information. However, low-tech measures such as brochures, public service announcements, and direct contact with local residents also are important to fostering awareness and response especially where access to ICT is limited or expensive (National Research Council, 2011).

Behavioral measures are among the suite of options that are integral to advancing climate adaptation. Government incentives can spark behavioral change. For example, to slow runoff into storm sewers and reduce flooding, a number of cities in the USA run "Disconnect your Downspout" programs to urge homeowners to redirect water from their roof into a storage tank or small wetlands. These programs will provide information to households and some offer rebates on supplies. Many poor and vulnerable communities have taken steps to adapt to changes in climate, particularly those in flood-prone areas. For instance, some local communities in Manila are increasing the number of floors in homes and building makeshift bridges (Porio, 2011). Behavioral adaptation can include livelihood diversification, which has long been used by African households to cope with climate shocks and spread risk (Section 22.4.5.2). Labor migration can be an important strategy for reducing vulnerability to different sources of stress as it helps households diversify their livelihoods (Banerjee et al., 2013). However, migration and relocation do have implications for family relations, health, and human security (see Sections 11.7.4, 12.4.2).

14.3.3. Institutional Options

Numerous institutional measures can be used to foster adaptation. These range from economic instruments such as taxes, subsidies, and insurance arrangements to social policies and regulations (de Bruin et al., 2009; Hallegatte, 2009; Heltberg et al., 2009). For instance, in the USA, post-disaster funds for loss reduction are added to funds provided for disaster recovery and can be used to buy out properties that have experienced repetitive flood losses and to relocate residents to safer locations, to elevate structures, and to assist communities with purchasing property and altering land-use patterns in flood-prone areas, as well as undertaking other activities designed to lessen the impacts of future disasters not only on habitation but also on more effective food production and other livelihoods (FEMA, 2010). Uptake of climate risk insurance is hindered by expensive premiums. The Caribbean Catastrophe Risk Insurance Facility (CCRIF) pools together country-level risks into a more diversified portfolio to offer lower premiums for immediate post-disaster responses (Section 29.6.2.2).

Laws, regulations, and planning measures such as protected areas, building codes, and re-zoning are institutional measures that can improve the safety of hazard-prone communities by designating land use to support resilience (Biderman et al., 2008; Bartlett et al., 2009). For example, marine protected areas (MPAs) have the potential to increase ecosystem resilience and increase recovery of coral reefs after mass coral bleaching (see Chapter 6, Box CC-CR). While zoning can be used to procure sites for low-income populations (Biderman et al., 2008; Bartlett et al., 2009; Satterthwaite and Dodman, 2009), if it increases property and housing values it also has the potential to exclude the poor from these areas. Legal rights can also determine adaptive capacity as well as access to resources. Land tenure security in Africa is widely accepted as being critical for enabling people to make longer-term decisions, such as changing farming practices (Section 22.4.6).

A number of funding and financial issues are linked to institutions. At the international level, agreements and donors have a critical role to play in promoting and supporting the allocation and flow of financial resources (OECD, 2011). For instance, the Adaptation Fund, which is set up under the Kyoto Protocol and funded through a levy on most Clean Development Mechanism (CDM) projects, is of particular importance to developing countries as it is pioneering the direct access mechanism which allows countries to access funds without having to work through a multilateral development agency. The direct access mechanism highlights the role of institutions in building and maintaining capacity, not just in the technical aspects of adaptation assessment and project design, but also in financial management and due diligence (Brown et al., 2011).

Effective governance is important for efficient operations of institutions. In general, governance rests on the promotion of democratic and participatory principles as well as on ensuring access to information, knowledge, and networks. Institutional strengthening and capacity building has been highlighted as a priority need in developing countries (Kumamoto and Mills, 2012). In assessment of river basin planning in Brazil, Engle and Lemos (2010) found that improving governance mechanisms appears to enhance adaptive capacity. Similarly water-trading schemes facilitated by new government measures reduced the impact of a major drought on the economy in Australia (Mallawaarachchi and Foster, 2009). The effectiveness of such approaches depends on both government will and capacity building among those affected.

In terms of national or local adaptation planning and policy making, Chapter 15 emphasizes that it can be challenging for governments to move beyond adaptation planning to implementation (Section 15.2.2). In an evaluation of one of the earliest national adaptation strategies for Finland, it was found that few measures had been implemented except in the water sector (see Box 23-2). Adaptation planning can occur at a number of spatial scales including at the national, regional, city, district, or local community level. Action plans can include a range of adaptation options including structural, social, and regulatory measures. For example, the city of Quito has proposed developing dams, encouraging a culture of rational water use, reducing water losses, and developing mechanisms to reduce water conflicts (Section 8.3.3.4). Table 25-5 lists various urban climate change adaptation options and their barriers to adoption. See also Section 15.3 on local adaptation plans.

Institutional adaptation options include the use of various decision-making and adaptation planning tools (Chapter 15) including iterative risk management (Chapter 2). There are various decision-making paradigms that can guide adaptation actions. For example, prominent institutional frameworks used for management of coastal areas include Integrated Coastal Zone Management (ICZM) and Adaptive Management (see Section 5.5.1.4). At the local scale, community-based adaptation refers to the generation and implementation of locally driven adaptation strategies through a learning-by-doing, bottom-up approach (Section 5.5.1.4). Community-based approaches to adaptation can also be mainstreamed into local or regional plans. Refer to Table 5-4 for a description of community-based adaptation options for coastal areas.

14.3.4. Selecting Adaptation Options

Selecting specific adaptation options can be challenging partly due to the rate, uncertainty, and cumulative impacts of climate change. How adaptation is framed will have an impact on how adaptation options are selected (Fünfgeld and McEvoy, 2011). Policy and market conditions may be a stronger driver of behavior than the observed climate itself (Berkhout et al., 2006). Also, rarely will adaptation options be designed to address climate risks or opportunities alone (IPCC, 2007b); instead actions will often be undertaken with other goals (such as profit or poverty reduction) in mind, while also achieving climate-related co-benefits. Gains in reduced vulnerability, enhanced resilience, or greater welfare will often be co-benefits generated as a result of changes and innovations driven by other factors (Khan et al., 2013). Rather than focusing on adaptation options addressing specific dimensions of climate change, more attention is being paid to mainstreaming climate change into wider government policy and private sector activities (see Sections 15.2.1, 15.5.1; Sietz et al., 2011a).

Selection and prioritization of adaptation options is important because not all adaptation options will be possible owing to constraints such as insufficient local resources, capacities, and authority (see Section 16.7). Furthermore, some adaptation options can be maladaptive if they foreclose other options (see Section 14.7). The viability of adaptation options is dependent on the time scale and climate scenario, emphasizing that selecting adaptation options is an iterative process.

A variety of systematic techniques have been developed for selecting options (e.g., see Section 15.4; De Bruin et al., 2009; Füssel, 2009; Ogden and Innes, 2009). Quantification and other systematic approaches to selecting options have many virtues. However, they also have limitations. For instance, most of these methodologies do not account for a range of critical factors such as leadership, institutions, resources, and barriers (Smith et al., 2009). For example, cost-benefit analysis of adaptation options requires valuation of non-market costs and benefits, which can be impractical (Section 17.3.2). Strategies dominating the early adaptation literature emphasized maintaining the current system and minimizing costs while achieving some form of benefit. For instance, no-regrets measures both reduce climate risk and provide other social, economic, or environmental benefits (Hallegatte, 2009). Risk management approaches often lead to no-regrets, low-regrets, or win-win options, while multi-criteria analysis (MCA) allows assessment of options against different criteria, as was used in the preparation of NAPAs (UNFCCC, 2011).

As ideas about adaptation have evolved, there has been a shift in ambition from traditional approaches that emphasize maintaining the status quo to more dynamic and integrative strategies (see also Sections 2.4.3, 14.1, 16.4.2, 20.5). Adaptive management places an emphasis on taking action and then using the lessons learned to inform future actions in order to make better informed, and often incremental, decisions in the face of uncertainty (Sections 2.2.1.3, 14.4). Lempert and Schlesinger (2000) have proposed that adaptation options should be robust against a wide range of plausible climate and societal change futures. Emerging trends in adaptation place an emphasis on the need for more transformational changes, which has a distinct logic that differs from traditional strategies (see Section 14.1).

As research and experience in the practice of adaptation grows, an ever increasing number of considerations have been advanced as being important in guiding the selection and sequencing of adaptation options. It is unlikely that every adaptation program can ever fully meet each of these considerations, especially as they are increasingly integrated with

Table 14-2 | Considerations when selecting adaptation options.

Consideration	Source (section) within this volume and selected references
Effective in reducing vulnerability and increasing resilience	9.3.5, 11.3; UNFCCC (2007); Brooks et al. (2011)
Efficient (increase benefits and reduce costs)	17.2, 17.4; Stern (2006); IFC (2010)
Equitable, especially to vulnerable groups	Chapter 12; 13.2.1; Huq and Khan (2006)
Mainstreamed/integrated with broader social goals, programs, and activities	15.1, 15.5; Agrawala (2005); Dowlatabadi (2007); Swart and Raes (2007); Agrawala and van Aalst (2008); Ayers and Dodman (2010)
Stakeholder participation, engagement, and support	12.3.1, 13.3, 15.1, 15.2; Swart and Raes (2007)
Consistent with social norms and traditions	12.3.1, 13.1.2; Moser (2006); O'Brien et al. (2007); Alexander et al. (2011)
Legitimacy and social acceptability	20.3.2; UNFCCC (2007); Brooks et al. (2011)
Sustainable (environmental and institutional sustainability)	13.1, 15.3; Brooks et al. (2007); Brown et al. (2011)
Flexible and responsive to feedback and learning	2.3.2, 2.3.3, 16.3, 20.2.3.2; Suarez et al. (2009); Agrawal (2010)
Designed for an appropriate scope and time frame	15.2.3.2, 16.1; Preston and Stafford-Smith (2009); Stafford-Smith et al. (2010); Brown et al. (2012)
Likely to avoid maladaptive traps	14.6; Grothmann and Patt (2005); Repetto (2008)
Robust against a wide range of climate and social scenarios	2.1.1, 17.2.5, 17.3.2; Lempert and Schlesinger (2000); Carmin and Dodman (2013)
Resources available (including information, finance, leadership, management capacity)	14.2.4; UNFCCC (2007); Martens et al. (2009); Brooks et al. (2011); Webb and Beh (2013)
Need for transformative changes considered	14.1; Wilbanks and Kates (2010); Park et al. (2012)
Coherence and synergy with other objectives, such as mitigation	14.6; Klein et al. (2007); UNFCCC (2007); Barnett and O'Neill (2010)

wider social or development goals, but Table 14-2 seeks to outline the most common considerations and point to sources in this volume and the literature for a discussion of some of the core issues.

14.4. Adaptation Assessments

14.4.1. Purpose of Assessments

Identifying adaptation needs requires an assessment of the factors that determine the nature of, and vulnerability to, climate risks (climate change assessments, climate impacts and risk assessments, and vulnerability assessments) and an assessment of adaptation options to reduce risks (adaptation assessment). The various types of climate change assessments differ in that they pursue different goals, are underpinned by different theoretical frameworks, and rely on different forms of data and ultimately may lead to different adaptation responses (Fünfgeld and McEvoy, 2011).

Assessments help decision makers understand the impacts, vulnerability, and adaptation options in a region, country, community, or sector. They are often characterized into "top-down" and "bottom-up" assessments. Top-down assessments are used to measure the potential impacts of climate change using a scenario and modeling driven approach. Bottom-up assessments begin at the local scale, address socioeconomic responses to climate, and tend to be location specific (Dessai and Hulme, 2004). They are often used to determine the vulnerability of different groups to current and/or future climate change and their adaptation options, using stakeholder intervention and analyzing socioeconomic conditions and livelihoods (UNFCCC, 2010). There are also policy-based assessments, which assess current policy and plans for their effectiveness under climate change within a risk-management framework (UNDP, 2004, 2005). The evolution of assessments has led to a more thorough assessment of society's ability to respond to risks through various adaptations, which can help guide allocation of adaptation resources (Füssel and Klein, 2006). In practice assessments have become increasingly complex, often combining elements of top-down and bottom-up approaches (e.g., Dessai et al., 2005). Decision makers use both in the policy process (Kates and Wilbanks, 2003; McKenzie Hedger et al., 2006).

14.4.2. Trends in Assessments

A variety of frameworks have been developed for the assessment of climate impacts, vulnerability, and adaptation (Fünfgeld and McEvoy, 2011). "Impacts-based" approaches focus primarily on the biophysical climate change impacts to which people and systems need to adapt. "Vulnerability-based" approaches focus on the risks themselves by concentrating on the propensity to be harmed, then seeking to maximize potential benefits and minimize or reverse potential losses (Adger, 2006; IPCC, 2007b). "Adaptation-based" approaches examine the adaptive capacity and adaptation measures required to improve the resilience or robustness of a system exposed to climate change (Smit and Wandel, 2006). In practice these approaches are interrelated, especially with regard to adaptive capacity (O'Brien et al., 2007). An evolution in the conceptualization of risk and vulnerability in the past decade has led to more holistic and integrated approaches to assessment, aiming toward a more systemic understanding of the complexity of human-environment interactions (Preston et al., 2011b).

The "standard approach" to assessment has been the climate scenario-driven impacts-based approach, which developed from the seven-step assessment framework of the IPCC (Carter et al., 1994; Parry and Carter, 1998): (1) define the problem (including study area and sectors to be examined), (2) select method of problem assessment, (3) test methods/conduct sensitivity analyses, (4) select and apply climate change scenarios, (5) assess biophysical and socioeconomic impacts, (6) assess autonomous adjustments, and (7) evaluate adaptation strategies. This approach dominated the assessment sections of the first three IPCC reports, and aims to evaluate the impacts of climate change under a given scenario and to assess the need for adaptation and/or mitigation to reduce any resulting vulnerability to climate risks (IPCC, 2007a). These frameworks are described as "first generation" or "type 1" assessment studies (Burton et al., 2002). The standard impact approach is often described as top-down because it combines scenarios downscaled from global climate models to the local scale with a sequence of analytical steps that begin with the climate system and move through biophysical impacts toward socioeconomic assessment (IPCC, 2007b). The process of downscaling of global climate models leads to issues of uncertainty and limited statistical confidence (Fünfgeld and McEvoy, 2011).

A new generation of scenario-based impact assessments has also emerged linking biophysical, economic, and social analysis tools. Refer to Section 2.3.2 for examples of large-scale and regional-scale scenario-based vulnerability assessments that have taken place linking biophysical and socioeconomic futures. In Europe, a study by Ciscar et al. (2011) estimated economic welfare losses over four sectors of 0.2 to 1% by the 2080s (Section 2.3.2.1). In Australia, socioeconomic considerations are beginning to be used to inform assessments of adaptive capacity and vulnerability (Section 25.3.2). A risk-based framework, based on the risk management approach, can also be used for assessing adaptation opportunities, constraints, and limits (Section 16.2). Economic assessments are also used to estimate the impacts of climate change, including distributional impacts and adaptation costs and benefits (Chapter 17).

The "second generation" vulnerability and adaptation assessments (Burton et al., 2002) pay greater attention to information around vulnerability to inform decisions on adaptation. They are characterized by the intensive involvement of stakeholders and the participation of vulnerable groups in decision making around adaptation options (Füssel and Klein, 2006; LDC Expert Group, 2012). Local projects often use participatory vulnerability assessment (PVA) methods. In Bangladesh, community-based adaptation has combined consensus-building and participatory rural appraisal (PRA) to assess needs of the communities and propose adaptation actions (Section 15.2.1). In activities by CARE, vulnerability assessments were undertaken with men and women's groups separately to ensure activities were gender sensitive (see Section 7.5.2). Participatory vulnerability assessments offer an opportunity to avoid maladaptation by involving stakeholders, for example, in a vulnerability assessment of tourism in the Mamanuca Islands in Fiji, where stakeholders were explicitly integrated into each step of the process (Section 29.8).

Adaptation assessments continue to evolve, but most syntheses now include "top-down" and "bottom-up" approaches, and include the assessment of both biophysical climate change risks and the factors that make people vulnerable to those risks. There is a shift toward integrating community-based planning into national adaptation plans. The Government of Nepal proposes "LAPA assessments" (Local Adaptation Plans of Action) that seek to integrate top-down and bottom-up models (Government of Nepal, 2011). There is also increasing attention to institutional capacity assessments and policy environments as key factors that can both drive vulnerability and also determine the type and success of different adaptation options. The generic elements of adaptation and vulnerability assessment are reflected in the the UK Climate Impacts Program (UKCIP) guidelines presented in Figure 14-2.

14.4.3. Issues and Tensions in the Use of Assessments

Adaptation and risk assessments give rise to various tensions, three of which are discussed here. The first is the adaptation paradox, which recognizes that climate change is a global problem while vulnerability

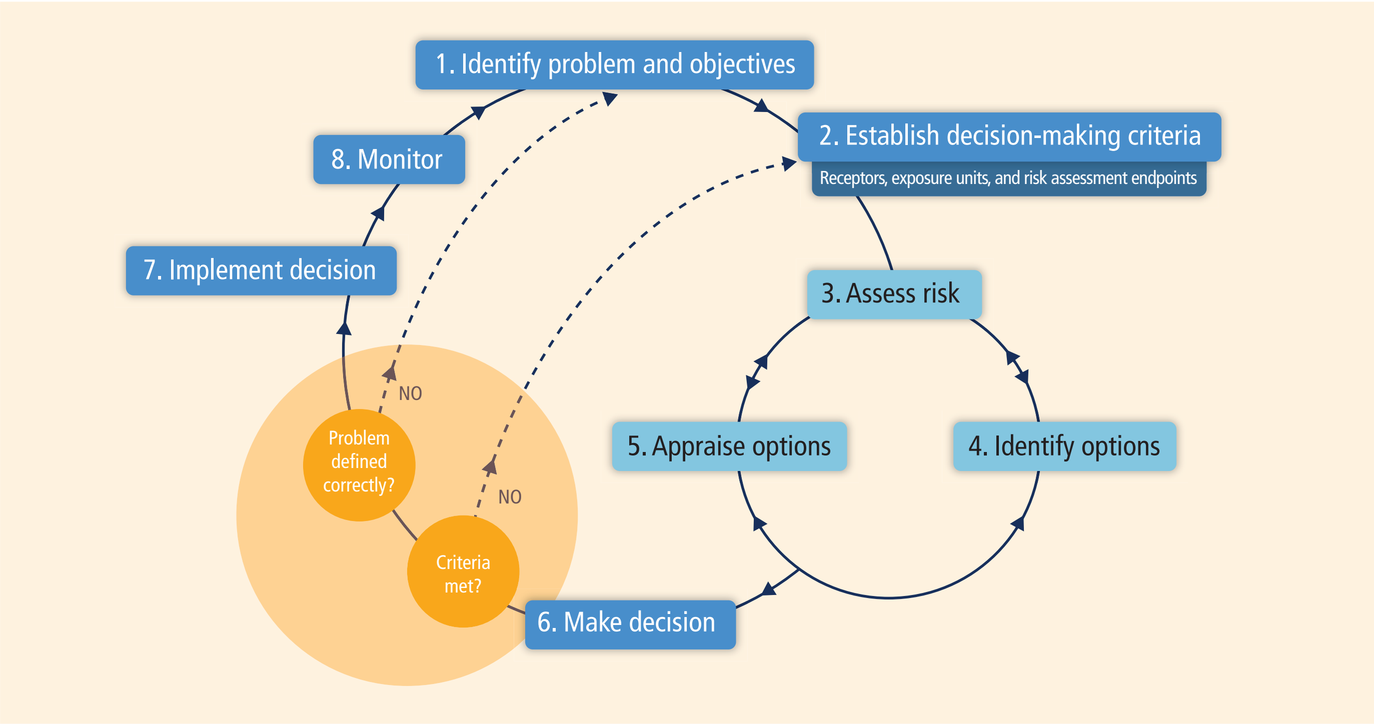

Figure 14-2 | A generic framework for vulnerability and adaptation assessments (UKCIP, 2011).

is locally experienced (Ayers, 2011). Top-down assessments of climate scenarios are deemed necessary in order to understand the climate change scenarios that render climate risk. However, the factors that make people vulnerable to climate risks are often locally generated, so require locally driven bottom-up analysis, while factors at the national and regional levels also determine vulnerabilities. Bottom-up analysis tends to prioritize groups based on factors related to poverty and development that drive vulnerability. Top-down assessments tend to prioritize those most exposed to climate risks. Analysis in Nepal that assessed both under-development and climate change impacts showed that, at the household scale, there was a strong correlation between local measures of poverty and vulnerability to climate change (Ghimire et al., 2010). However, when indicators were aggregated at district scale, the correlation was weaker—even when the vulnerability index used included poverty as a proxy for adaptive capacity alongside climate hazard risk and exposure (Ghimire et al., 2010).

There are also tensions around ownership and participation. Assessments managed under global climate change governance structure of the UN Framework Convention on Climate Change are developed under an "impacts-based" paradigm (Burton et al., 2002). This impacts-based approach requires external scientific and technological expertise for defining climate change problems, and formulating technological adaptation solutions, based on specific knowledge of future climate conditions. Such assessments are necessarily "top-down" because this expertise exists at the global and national level. At the local level, the capacity to adapt is based on the underlying securities that determine vulnerability to these impacts in the first place (Adger et al., 2003a). Accessing this information requires "bottom-up" and participatory assessments that engage local vulnerable people. These vulnerable groups and institutions often do not have access to the climate impacts science necessary to fully apply top-down impacts-based assessments. Some places also do not have accurate historical weather data, making it difficult to validate climate trends and models and hence develop evidence-based scenarios of what will happen with any degree of accuracy (Conway, 2009).

The numerous assessments that have been carried out have led to increased awareness among decision makers and stakeholders of climate risks and adaptation needs and options. But this awareness is often not translated into the implementation of even simple adaptation measures within ongoing activities or within risk management planning. There is a bottleneck in adaptation assessments, which may need to be overcome by linking more directly to particular decisions and tailoring the information to local contexts to facilitate the decision-making process (Preston and Stafford Smith, 2009; Brown et al., 2011). Specific techniques such as decision scaling, which seeks to understand which climate conditions would result in hazardous conditions of concern for particular stakeholder groups, are a step in this direction (Brown et al., 2012; Moody and Brown, 2012). Decision support must recognize that human psychological dimensions play a crucial role in the way people perceive risks and make decisions (Section 2.2.1.2). Impacts and adaptation options will also have to be successfully communicated to the local scale. One example of this is local-scale visualization of impacts and adaptation measures, as has taken place in British Columbia, Canada (see Section 2.2.1.3). Use of ICT tools can foster new ways to assimilate or translate information (see Box 15-1). Vulnerability mapping, including the use of geographic information systems (GIS), can help stakeholders to visualize the impacts of climate change on the landscape, while integration with participatory processes can facilitate learning and deliberation (Preston et al., 2011a).

14.4.4. National Assessments

Under the UNFCCC, all parties are encouraged (Annex 1 countries are required) to report on activities in relation to "vulnerability assessment, climate change impacts and adaptation measures" (FCCC/CP/1999/7). Parties are encouraged to use the IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations (Carter et al., 1994) and the UNEP Handbook on Methods for Climate Change Impacts Assessment and Adaptation Strategies, which focuses on the impacts of sea level rise and uses the seven-step assessment framework (described previously). Annex 1 countries are due to submit their sixth Communications by 2014 and most non-Annex I countries are due to have submitted at least one Communication; some are on their fifth. As such, National Communications have formed the first avenue for assessing and reporting on climate risk and vulnerability assessments at the national level. Most initial National Communications to the UNFCCC produced by developing countries were first-generation vulnerability assessments, which did not seek to assess the feasibility of implementing adaptations (Füssel and Klein, 2006). Undertaking such assessment is resource intensive, underscoring the need for further resources, training, and expertise.

There is a range of emerging national experiences on adaptation and vulnerability assessments. For coastal areas under sea level rise, a summary of the results from coastal vulnerability assessments is shown in Table 5-5. Such assessments show that vulnerability is highly dependent on the greenhouse gas (GHG) mitigation scenario. In Kenya, a study by the Stockholm Environment Institute (SEI) estimated the economics of climate change under a range of scenarios (see Figure 22-6) and estimated that, by 2050, more than 300,000 people could be flooded per year under a high-emissions scenario. In 2012, the UK's first Climate Change Risk Assessment (CCRA) was undertaken based on a similar framework to that shown in Figure 14-2, to assess risks in and across eleven sectors to inform priorities for action and appropriate adaptation measures (DEFRA, 2012).

National Adaptation Programmes of Action are designed as a vehicle for Least Developed Countries (LDCs) to communicate their most "urgent and immediate adaptation needs" to the UNFCCC for funding from the Least Developed Countries Fund (LDCF). "Urgent and immediate needs" are defined as those for which further delay in implementation would increase vulnerability or increase adaptation costs at a later stage (LDC Expert Group, 2009). The approaches adopted for vulnerability assessment under NAPAs vary. Although the guidelines call for more participatory and "bottom-up" mechanisms to be adopted, time and funding limitations have meant that often the NAPA process remains largely top-down, focused on impacts and consulting the communities only to verify this information (Huq and Khan, 2006; Ayers, 2011). Moreover, available financial resources were too limited to fully assess and address the needs of all sectors and all vulnerable regions of the country (LDC Expert Group, 2012; see also Section 15.2.1.2).

Frequently Asked Questions

FAQ 14.1 | Why do the precise definitions about adaptation activities matter?

Humans have always adapted to changing conditions: personal, social, economic, and climatic. The rapid rate of climate change now means that many groups, ranging from communities to parliaments, now have to factor climate change into their deliberations and decision making more than ever before. Having a term and working definition is always useful in discussing how to tackle a challenge as it helps define scope. Is adaptation all about minimizing damage or are there opportunities as well? Can adaptation proceed only through deliberately planned actions focused specifically on adaptation to climate change? How much must be known about future climates to make decisions about adaptation? How does the adaptation of humans systems differ from adaptation in natural systems? Can adaptation to climate change be distinguished from normal development and planning processes? Need it be? Are we adequately adapted to current climates, or do we have an "adaptation deficit"? The phrase "maladaptation" immediately turns thoughts to how could plans go wrong and possibly cause greater suffering. A definition does not answer all these questions but it provides a framework for discussing them.

There is also a political reason for needing a precise definition of adaptation. Developed countries have agreed to bear the adaptation costs of developing countries to human-induced climate change and that these funds should represent "new and additional resources,"[4] and the Cancun Agreement and subsequent discussions suggest that for adaptation these funds could amount to tens of billions US$ per year.[5] In most cases adaptation is best carried out when integrated with wider planning goals such as improved water allocation, more reliable transport systems, and so forth. How much of the cost of upgrading a coastal road that is already subject to frequent damage from bad weather should be attributed to normal development and how much to adaptation to climate change? A precise answer may never be possible but the closer we agree as to what constitutes adaptation, the easier it will be to come to workable agreements.

Under the Cancun Adaptation Framework (CAF), a process was established to enable LDC parties to formulate and implement National Adaptation Plans (NAPs). NAPs are intended to build on NAPAs but shift the focus toward identifying medium- and long-term adaptation needs and developing and implementing strategies and programs to address those needs. NAPs are intended to facilitate the integration of climate change adaptation into relevant national and subnational development and sectoral planning (LDC Expert Group, 2012). Other developing country parties are also invited to employ the modalities formulated to support the national adaptation plans in the elaboration of their planning efforts. Early guidelines (LDC Expert Group, 2009) propose a country-specific approach tailored to national circumstances, mixing top-down policy-first assessments with bottom-up approaches. Recent guidelines propose that this should be non-prescriptive and should facilitate country-driven, gender-sensitive, participatory action, taking into consideration vulnerable groups, communities, and ecosystems (LDC Expert Group, 2012). Refer also to Sections 2.4.3 and 15.2.1.2 for further details of national and subnational adaptation planning including NAPAs and NAPs.

14.5. Measuring Adaptation

Adaptation has tended to lag behind mitigation efforts both in research and in the climate negotiations. In part this is because adaptation and development specialists, governments, NGOs, and international agencies have found it difficult to clearly define and identify precisely what constitutes adaptation, how to track its implementation and effectiveness, and how to distinguish it from effective development (Burton et al., 2002; Arnell, 2009; Doria et al., 2009). A contributing reason is that adaptation has no common reference metrics in the same way that tonnes of GHGs or radiative forcing values are for mitigation. This section seeks to explore the feasibility of finding metrics for measuring adaptation effectiveness.

The search for metrics[6] for adaptation will remain contentious, with many alternative uses competing for attention. This is inevitable as there are multiple purposes and viewpoints in approaching the measurement of adaptation (Hulme, 2009). Brooks et al. (2011) asked "what constitutes successful adaptation" and suggested that the criteria by which success

[4] Bali Action Plan, 2007; FCCC/CP/2007/6/Add.1.

[5] Cancun Agreements 2010, FCCC/CP/2010/7/Add.1, paras 98 & 102.

[6] There is no consistent use of the terms metric, measure, and indicator in the literature. Here we try to stay as close as possible to the dictionary meanings (although they overlap). A measure is the amount or degree of something, that is, a description of its (presumably current) state. A metric is often a group of values (measures) that taken together give a broader indication of the state or the degree of progress to some desired state. An indicator is a sign, or estimate of the state of something and often of the future state of something. Most often in seeking to understand the state of vulnerability or adaptation, etc., we need a metric (i.e., a group of measures) and we use the term in that way. In describing the components of a metric we will give preference to the term indicator over measure.

might be assessed include feasibility, efficacy/effectiveness, efficiency, acceptability/legitimacy, and equity (derived from Yohe and Tol, 2001; Adger et al., 2005; Stern, 2006), to which they added sustainability (Fankhauser and Burton, 2011). Effective integration and coherence with wider national policies and development goals is another often sought criterion (World Bank, 2010). Also institutions, communities, and individuals value things differently and many of those values cannot be captured in a comparable way within metrics (Adger and Barnett, 2009).

At least three uses of metrics for adaptation are relevant, each requiring different characteristics of the indicators used. The first use seeks metrics to help determine the need or determinates of that need for adaptation. These metrics usually focus on measuring vulnerability, but that term is not well defined. For example, Hinkel (2011) identifies six uses that vulnerability indicators are sometimes expected to serve and concludes that they can truly serve only their core purpose, that is, to identify vulnerable people, communities, and regions. Further, even with metrics focusing on vulnerability the goal often is not to produce a score or rating to identify vulnerable groups but to elucidate information on the nature of vulnerability and to better identify adaptation options (Smit and Wandel, 2006; Sietz et al., 2011b). The second use of metrics relates to measuring and tracking the process of implementing adaptive actions, such as spending on coastal protection, the number of early warning plans implemented as part of a program, or the number of agricultural specialists with appropriate training in climate risks. Here the selection of appropriate metrics is usually less contentious but there is disagreement as to how much they capture adaptation rather than normal development. The third use of metrics relates to measuring the effectiveness of adaptation such as in monitoring and evaluation. This set is essential to help measure progress and provide feedback on the effectiveness of actions, but is among the most difficult to identify as adaption outcomes take time to become identifiable and are often subject to evolving conditions and objectives.

14.5.1. What Is to Be Measured?

The measurement of vulnerability is central to many adaptation metrics and initially it was approached from an impacts point of view. Here vulnerability is usually defined as a function of (1) exposure to specific hazards or stressors, (2) sensitivity to their impacts, and (3) the target population's capacity to adapt (IPCC, 2001, Chapter 17). This approach continues to be used as the basis of many assessments and adaptation prioritization efforts. Recently the emphasis has moved from better defining exposure and potential impacts to a better understanding of the factors that affect societies' sensitivity to those impacts and their capacity to adapt. This reflects the increasing recognition of the importance of considering social vulnerability alongside biophysical vulnerability. Various terms have been used to describe these different emphases including biophysical versus social vulnerability, outcome versus contextual vulnerability (Section 14.2.1.1; Eakin and Luers, 2006; Füssel and Klein, 2006; Eriksen and Kelly, 2007; Füssel, 2010), and scientific framing versus a human-security framing of vulnerability (O'Brien, 2007). O'Brien et al. (2007) argue that scientific and human-security frameworks affect the way we approach adaptation, with the scientific framework leading to building local and sectoral capacity to make changes rather than address the fundamental causes of vulnerability, or climate change itself, within their broader geopolitical and economic contexts.

Other questions also arise even within a given conceptual framework for considering vulnerability. A system of measurement is usually developed to allow comparisons between different places, social groups, or sectors of activity, although experience repeatedly cautions us to be careful in doing so (Schröter et al., 2005). The challenge is as much of integration across widely differing research domains and traditions (Polksy et al., 2007). Also, a system's vulnerability is not static but can respond rapidly to changes in economic, social, political, and institutional conditions over time (Smit and Pilifosova, 2003; Smit and Wandel, 2006). Much of the effort in relation to estimating social vulnerability is reviewed in Cutter et al. (2009).

It has also been suggested that a framework based on the concept of resilience is more appropriate than a vulnerability framework in many contexts (see IPCC, 2012, Chapter 2 and Section 8.3.3 for more details). For example, in a development context resilience "evokes positive and broad development goals (e.g., education, livelihood improvements, food security), includes multiple scales (temporal and spatial) and objectives, better captures the complex interactions between human societies and their environments, and emphasizes learning and feedbacks" (Berkes, 2007; Moss et al., 2012, p. 6). A resilience approach also leads to more focus on interactions between social and biophysical systems (Nelson et al., 2007). However, others feel that resilience promotes too great a focus on the return of the overall system to pre-impact conditions and not enough on the human agents and their need to adapt to changing conditions (Nelson et al., 2007; IPCC, 2012, Section 8.3.3). The concept of resilience has been difficult to apply in practice and is particularly resistant to attempts to establish commonly accepted sets of indicators. Some (e.g., Klein et al., 2003) have suggested that resilience has become an umbrella concept that has not been able to support effectively planning or management.

Recently Brooks et al. (2011) have outlined a framework tracking adaptation that combines the establishment of upstream metrics to assess how well risks are being managed by institutions, and downstream metrics to track whether the interventions are reducing the vulnerability of affected groups. The upstream metrics would focus on assessments of institutional capacity, managerial performance, and integration of climate risk management into planning processes and tracking and feedback processes. The downstream metrics would focus on indicators to track development performance and changes in vulnerability. Attribution of these changes to particular interventions would be desirable but not essential to track progress.

But understanding vulnerability does not necessarily translate to effective adaptation. Smit et al. (2001), Osman-Elasha et al. (2009), and others have suggested that the focus should be on increasing adaptive capacity within the context of the full range of biophysical and socioeconomic stressors. However, as the scope of the metrics is widened to include aspects of development and sustainability they often become less suitable for other purposes such as helping to identify "the full and additional costs of adaptation" (McGray et al., 2007). In deriving indices of vulnerability there are again several broadly different approaches. One is to deductively identify indicators that theoretically should be strongly

Table 14-3 | Criteria for the selection of indicators (based on multiple sources).

Criterion		Explanation
Validity	Not ambiguous	Agreement on the direction of influence between the indicator and what is sought to be measured (target measure)
	Well founded	Based on a tested theoretical framework
	Well defined	So that unwitting errors are minimized (e.g., measuring a family or a household)
	Purpose known	This helps fix problems in data collection; misunderstandings between different collecting agencies, etc.
	Accurate	Measuring what it should, and responds quickly
	Precise	Statistical variation between measurements is low
	Quality checked	Ideally subject to independent checking; is there a cross checking mechanism?
	Transparent	Information source and control of information flow is known
	Honest	There should be no rationale or opportunity for individuals to manipulate or distort the data (e.g., manipulating rain-gauges used for weather index insurance)
Value	Comprehensible	Relatively easy for user to understand
	Relevant	Applicable to a wide range of circumstances (geographic, social, economic)t
	Responsive	Can measure usefully small changes in the target measure
	Actionable	The quality/quantity of what is being measured can be affected by human appropriate actionst
	High information content	Usually quantitative is more useful than qualitative, than binary data; and real measurements more useful than modeled estimates or expert judgment
	Disaggregatable	Can the indicator be collected for specific groups (e.g. children, women, and men)
	Participatory	Can local people be involved in the data collecting; does the data help inform and possibly empower them
Data	Available	Data is publicly and easily available; affordable
	Homogenous	Data collection is consistent across location and time, including matching season or time-of-day if necessary
	Periodic	Data is collected at a frequency that is suitable for tracking changes
	Long time course	Data has been consistently collected for some years
	Spatial coverage	Spatial coverage must be sufficient to provide a fair representation of the measure (e.g. density of rain gauges)

related to vulnerability (e.g., Dolan and Walker, 2003; Polsky et al., 2007), while the other is inductive and uses observed data to seek correlations between indicators and observed consequences of vulnerability, such as the number of people killed or affected by climate-related events in recent history. There is some commonality in identifying the desirable criteria for selecting indicators, and though no list can ever be complete, Table 14-3, based initially on Perch-Nielsen (2010), seeks to bring together some of the most common criteria.

14.5.2. Established Metrics

Numerous metrics continue to be prepared for a variety of purposes and at scales ranging from estimating the vulnerability of individuals and communities to comparing countries. Several reviews, including Moss (2001, 2012), Srinivasan and Prabhakar (2009), and Prabhakar and Srinivasan (2011), discuss both the design and effectiveness of many of the existing proposals for adaptation metrics.

14.5.2.1. Vulnerability Metrics

Eriksen and Kelly (2007) found strong divergence among five metrics (or indices) for comparing national vulnerability published over the period 1995–2003: the Dimensions of Vulnerability of Downing et al. (1995); the Index of Human Insecurity (IHI) of Lonergan et al. (1999); the Vulnerability-Resilience Indicators of Moss et al. (2001); the Environmental Sustainability Index of the World Economic Forum (2002); and the Country-Level Risk Measures of Brooks and Adger (2003). Between them, 29 indicators were used, with only five indicators appearing in more than one study. They were able to compare the 20 countries ranked as most vulnerable from three of the studies and found little overlap, with only five countries ranked in the top 20 in more than one study. However, it must be noted that the metrics were developed at different times and for different purposes. They concluded that the indices focused on measuring a snapshot of aggregate conditions rather than on delivering guidance on societal processes that can be targeted to reduce vulnerability.

There are a series of disaster-related indices designed to assess relative risks across countries and regions, and to provide benchmarks on which to assess progress. Among them are the Disaster Risk Index (UNDP, 2004); Hotspots Index (Dilley et al., 2005); the Americas Index (Cardona, 2005); and an index for South Asia (Moench et al., 2009). Again, there has been little effort to further analyze, validate, or compare these metrics.

14.5.2.2. Metrics for Resource Allocation

Vulnerability indices have usually been selected to better understand the drivers of vulnerability or to compare countries, regions, communities, and so forth in terms of the risks they face from climate change and their capacity to deal with them. This is not necessarily the same as designing an allocation index or rule to be used to allocate limited resources equitably and efficiently among entities (countries, regions or other administrative groups, or different proponents of adaptation). For allocation, vulnerability and coping/adaptive capacity might be expected to remain a core consideration, but so also should the relative costs of implementation in relation to the potential benefits and the ability of the recipients to absorb the funding and implement policies and projects to actually achieve the projected benefits (UNFCCC, 2007; Parry et al., 2009; Wheeler, 2011).

One of the longest running and prominent uses of metrics in funding is the World Bank's process of allocating IDA concessional funds to developing countries, which faces many issues analogous to the same process for adaptation. The World Bank uses the Country Policy and Institutional Assessment (CPIA) based on 16 criteria, many qualitative, to estimate the extent to which a country's policy and institutional framework supports sustainable growth and poverty reduction, and consequently the effective use of development assistance. These criteria are the main components used to calculate a Country Performance Rating, which in turn is a major component, along with population and recent performance measures, in calculating allocations to the poorest developing countries with long-term, no interest (IDA) loans. The CPIA and the ultimate IDA allocation formulae are controversial, much debated (Alexander, 2010), and often fine-tuned (IEG, 2009) but still commonly used as a reference point for this type of procedure (GTZ, 2008).

An explicit example of the use, and non-use, of adaptation metrics was in establishment of the Pilot Program for Climate Resilience (PPCR). The governing body, made up of contributors, recipients, and other stakeholders, set up an independent expert group to make recommendations as to which countries might be included as pilots within the approximately US$1 billion program (Climate Investment Funds, 2009). The expert group refrained from using a simple index, but instead country selection was done across nine regions and each based on a suite of indicators appropriate for the region using expert judgment. It is interesting to note that on moving to the next step of deciding on allocation of financial resources to the selected pilot countries the governing body of the PPCR chose not to use an approach based on indicators, but to provide guidance to the countries of the possible range of funding and to base allocations on the quality of the proposals brought forward (Climate Investment Funds, 2009). Similarly, none of the other governing bodies of international adaptation funding mechanisms (e.g., the Global Environment Facility, the Adaptation Fund) has chosen to use a defined set of metrics within their decision making.

Wheeler (2011) has developed an index of vulnerability based on weather-related disasters, sea level rise, and agricultural productivity. The index can be adjusted according to user preferences to develop allocation formulas based only on biophysical vulnerability, further adjusted for economic development and governance, and finally for project costs and probability of success. Klein and Möhner (2011) have discussed the options for the Green Climate Fund based on experience to date and conclude that science cannot be relied on for a single objective ranking of vulnerability.

14.5.2.3. Metrics for Monitoring and Evaluation

The IPCC's Fourth Assessment Report provided little discussion of the role of evaluation and monitoring of adaptation responses as a component of building adaptive capacity (Adger et al., 2007). Preston et al. (2011a) identify three specific roles of evaluation: (1) ensuring reduction in societal and ecological vulnerability, (2) facilitating learning and adaptive management, and (3) providing accountability for adaptation investments (see also GIZ, 2011). A central challenge in developing robust monitoring and evaluation frameworks for adaptation is the existence of multiple, valid points of view that can be used to evaluate adaptation actions and their continuing effectiveness (Gagnon-Lebrun and Agrawala, 2006; Perkins et al., 2007; Füssel, 2008; Smith et al., 2009; Ford et al., 2011; Preston et al., 2011b). This challenges the selection of appropriate metrics for the monitoring and evaluation of adaptation and its contribution to vulnerability reduction (Burton and May, 2004; Gagnon-Lebrun and Agrawala, 2007; McKenzie Hedger et al., 2008; Ford et al., 2011).

One of the central unresolved tensions in progressing evaluation is the relative merit of comparatively easy and objective targeting of the completion of the processes and outputs needed to implement an adaptation program versus the outcomes, such as changes in livelihoods or reduction in risks. Assessment of outcomes is less objective, subject to whether appropriate circumstances occur (e.g., that floods occur so that risk reduction can be demonstrated) and usually take much longer to establish. Preston et al. (2011b) suggest the evaluation of adaptation processes may be a more robust approach to evaluation, owing to the difficulties in attributing future outcomes to adaptation strategies and the long-time lags that may be needed to assess the performance of a particular strategy (Berkhout, 2005; Dovers and Hezri, 2010; Ford et al., 2011). The OECD analyzed the monitoring and evaluation processes across 106 adaptation projects across six development agencies and found that Results Based Management and Logical Framework approaches dominated, as they do in normal development projects (Lamhauge et al., 2011). They also drew attention to the need for appropriate baselines and complementary sets of indicators that track not just process and implementation, but also the extent to which targeted changes are occurring. Monitoring programs themselves will need careful design to ensure that they remain in place over the long time frames needed for the outcomes to be identified; that they contain incentives for beneficiaries to comply with conditions; and that compliance itself does not impose undue burdens.

A number of national and international organizations have guides to monitoring and evaluating adaptation activities (McKenzie Hedger et al., 2008; UNDP, 2008; WRI, 2009; World Bank, 2010; GIZ, 2011). These guides tend to focus on the wider framework of identifying and managing adaptation-related activities and within that the criteria for the selection of metrics for monitoring and evaluating those activities. These issues are dealt with in Chapters 15 and 16.

14.5.3. Validation of Metrics

The practice of developing and applying metrics in adaptation has been subject to much scrutiny. Eakin and Luers (2006) express serious concerns about national-scale vulnerability assessments ranging from the quality of the available data, the selection and creation of indicators, the assumptions used in weighting of variables, and the mathematics of aggregation. Nevertheless metrics will continue to be used and the challenge is to identify and maintain basic standards of best practice.

One of the most comprehensive attempts to validate a system for measuring important components of adaptation is that of Brooks et al. (2005). They used the probability of national climate-related mortality from the CRED database of climate-related disasters[7] as a proxy for risk and selected a set of 46 social, governance, economic, and biophysical measures as indicators of social vulnerability. They found that 11 were effective indicators of mortality rates and these were confirmed as useful by a small focus group of seven adaptation experts. These experts also ranked the variables in terms of their perception of their usefulness leading to a total of 12 different rankings to which was added an equal ranked set to give 13 measures of vulnerability. Countries were then scored against these 13 rankings, and the number of times a country appeared in the top quintile of countries in a particular ranking was used as an indicator of its overall vulnerability.

Progress continues to be made in the methodologies of deriving vulnerability metrics. For example, Rygel et al. (2006) have demonstrated the value of using a Pareto method for combining scores from a collection of indices without having to apply either implicit or explicit weightings. Alcamo et al. (2008) sought to increase the consistency of incorporating expert opinion on different disciplinary approaches (sociology, environmental psychology, economics, and political science) to the estimate of vulnerability, in this case of drought events, in three regions. Based on inference models about what contributes to vulnerability to drought and using fuzzy set theory (Eierdanz et al., 2008) to compute susceptibilities, they were able to show that high combined susceptibilities were associated with water stress crises.

Perch-Nielsen (2010) developed an index to estimate the vulnerability of beach tourism using a systematic approach by establishing a framework to identify the types of indicators needed and a systematic approach to identify indicators that covered the range of countries and time scales. The derivation of the index from the separate indicators was also subjected to robustness (sensitivity) testing to determine the most appropriate methods of scaling and combining the measures.

14.5.4. Assessment of Existing and Proposed Metrics for Adaptation

Srinivasan and Prabhakar (2009) conducted a wide-ranging stakeholder survey to assess the attitudes to, and requirements for, indicators of adaptation. Stakeholders agreed that no single metric can capture the multiple dimensions of adaptation and that refinements of methodologies (e.g., rationale for index selection, aggregation methods, and data checking) are badly needed. Preston et al. (2009) have suggested that, rather than seeking particular metrics, researchers should focus on developing rigorous processes for selecting metrics that can be applied in a range of contexts. But metrics for adaptation remain a necessity. Their derivation challenges the adaptation community to clarify its goals, conceptual models, definitions, and applications. But both theory and practice have shown indices alone are not sufficient to guide decisions on which adaptation actions to take, on how to modify sustainable development activities, or on resource allocation. Downing (2003) noted that the climate change community was far from adopting common standards, paradigms, or analytic language. This still appears to be true, making the search for commonly accepted metrics, even within well-specified contexts, a challenging task.

14.6. Addressing Maladaptation

The adaptation literature is replete with advice to avoid maladaptation, but it is less clear precisely what is included as "maladaptation." In a general sense maladaptation refers to actions, or inaction that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future (see Glossary). For example, the construction of well-engineered climate-resilient roads designed to withstand current and future climate extremes may foster new settlement into areas highly exposed to the impacts of future climates; or increased water harvesting upstream to cope with erratic rainfall may harm and reduce the opportunities for communities downstream to manage their own risks. Actions that are potentially maladaptive need not be inadvertent (as in the IPCC AR3 and AR4 definition), nor be "taken ostensibly to avoid or reduce vulnerability to climate change" (Barnett and O'Neill, 2010) as the actions may be assessed as appropriate in the context of the full range of climate and non-climate considerations and pressures that apply to the decision. There should be clarity as to what is maladaptive action, or lack of action, lest the avoidance of potential maladaptation becomes a barrier to effective implementation of adaptation. In the road example above, the immediate and multiple benefits to the community of a reliable road system (including as evacuation route in floods, etc.) might be judged as outweighing the longer term risk of inappropriate settlement patterns (Lamhauge et al., 2011). This may be seen as an example of an "unavoidable" *ex post* maladaptation (see Section 16.3.6.1) as it is an appropriate decision based on the information and circumstances at the time. The true maladaptation in this case would be the failure to implement appropriate incentives or regulations to avoid vulnerable settlements in the highly exposed areas.

The wide range of actions and circumstances that have been described as maladaptive demonstrates the complexity of the concept and terminology. Thomsen et al. (2012) describe actions that are not respectful of the intrinsic integrity and internal self-regulation of social-ecological systems as manipulative and likely to prove maladaptive. Their example is the management of Noosa Beach in northern Australia, where the coastline is characterized by cycles of erosion and depletion of beach sands. Rather than enhance the self-regulatory processes and adapting by managed retreat and expansion according to the cycle, management has sought to maintain a static beach profile through hard constructions and beach nourishment. Niemeyer et al. (2005) also describe the state of individual beliefs about climate change that might change from adaptive to inaction and possibly maladaptive behaviors as the perceived magnitude of climate change increases, while Eriksen et al. (2011) and Brown (2011) discuss avoiding outcomes that are

7 CRED, the Centre for Research on the Epidemiology of Disasters, has maintained a database of disasters, including those that are climate related. Rationale, methodologies, and data are available at http://www.cred.be/.

essentially maladaptive as they run counter to sustainable development goals.

14.6.1. Causes of Maladaptation

Maladaptation arises in many forms but several broad causes can be identified. Actions that may benefit a particular group, or sector, at a particular time may prove to be maladaptive to those same groups or sectors in future climates or to other groups or sectors in existing climates. For example, some development policies and measures that deliver short-term benefits or economic gains but lead to greater vulnerability in the medium to long term, such as in cases where the construction of "hard" infrastructure reduces the flexibility and the range of future adaptation options (Adger et al., 2003b; Eriksen and Kelly, 2007; OECD, 2009), or the failure to encompass the full range of risks in the design of new structures, such as the effects of increasing storm surge in the design of a coastal defense system (UNFCCC, 2007). Adaptation efforts aimed at armoring the coastline may result in coastal erosion elsewhere while building levees along a flood-prone area provides protection to coastal population and infrastructure but might encourage unwanted development within that area, often accentuated by an exaggerated sense of safety (Grothmann and Patt, 2005; Repetto, 2008; National Research Council, 2011) and the levees may increase damage when they fail, as in Bangladesh in 1999 and New Orleans in 2003 (Huq and Khan, 2006; Masozera et al., 2007; Pouliotte et al., 2009). Similarly, agricultural policies that promote the growing of high-yielding crop varieties through subsidies with the objective of boosting production and increasing revenues may achieve these objectives in the short term, but will also reduce agro-biodiversity and increase exposure and vulnerability of mono-crops to climate change and finally undermine the adaptive capacity of farmers in the long term (World Bank, 2010).

Another cause of maladaptation is the failure to account for multiple interactions and feedbacks between systems and sectors leading to inadequate or inaccurate information for developing adaptive responses and strategies that are maladaptive (Scheraga et al., 2003; Satterthwaite et al., 2009; Pittock, 2011). An assessment of the downstream impacts of upstream rainwater harvesting in a semiarid basin in southern India showed that, once the full range of externalities were accounted for, the net benefits were insufficient to pay back investment costs (Bouma et al., 2011). Similarly, the conversion of coastal mangroves into shrimp farms may lead to increased economic productivity and improved livelihoods, but could also lead to increased vulnerability to flooding and storm surges (Klein, 2010). Maladaptation may also occur if the true potential of an option or a technology is unduly over-emphasized, making it over-rated. Floating gardening has been suggested as an example in this connection (Irfanullah, 2009, 2013). Further examples of the range of maladaptive actions across a range of sectors and regions in this report are outlined in Table 14-4.

14.6.2. Screening for Maladaptation

Five dimensions of maladaptation were identified by Barnett and O'Neill (2010), including actions that, relative to alternatives: (1) increase emissions of GHGs, (2) disproportionately burden the most vulnerable, (3) have high opportunity costs, (4) reduce incentives and capacity to adapt, and (5) set paths that limit future choices. These dimensions are useful pointers to the potential for maladaptation but their application depends on subjective assessments. The first suggests that any action that increases GHG emissions is maladaptive, whereas a judgment on the relative benefits and dis-benefits will need to be made in such cases; the second turns on the interpretation of "disproportionately;" and the third on "high" and on how opportunity costs are compared with current benefits. The dimensions were used by Barnett and O'Neill (2010) to describe maladaptive potential of the Wonthaggi desalinization plant to improve water supply to Melbourne, Australia. The plant was included as part of a wider water management plan for Melbourne that includes both demand- and supply-side management and incentives (Heffernan, 2012; Porter, 2013). Barnett and O'Neill (2010) argue that the plant (1) will increase GHG emissions (even if the planned wind power

Table 14-4 | A selection of examples of actual or potential maladaptive actions from this report.

Broad type of maladaptive action	Examples in AR5
Failure to anticipate future climates. Large engineering projects that are inadequate for future climates. Intensive use of non-renewable resources (e.g., groundwater) to solve immediate adaptation problem	22.3, 22.4.8.5
Engineered defenses that preclude alternative approaches such as EBA	Box CC-EA; 15.2.2
Adaptation actions not taking wider impacts into account	22.4.5.8, 25.4.2, and 26.9.4
Awaiting more information, or not doing so, and eventually acting either too early or too late. Awaiting better "projections" rather than using scenario planning and adaptive management approaches	7.5.1.2.2, 8.5.2, and 16.5.2
Forgoing longer term benefits in favor of immediate adaptive actions; depletion of natural capital leading to greater vulnerability	13.2.1.3; 22.4.5.8; 25.9.1
Locking into a path dependence, making path correction difficult and often too late	16.3.2; FAQ 25.1
Unavoidable ex post maladaptation, e.g., expanding irrigation that eventually will have to be replaced in the distant future	17.5; see also 5 and 6 above
Moral hazard, i.e., encouraging inappropriate risk taking based, e.g., on insurance, social security net, or aid backup	17.5 and 29.8
Adopting actions that ignore local relationships, traditions, traditional knowledge, or property rights, leading to eventual failure	12.3, 12.5.2; 26.9.4
Adopting actions that favor directly or indirectly one group over others leading to breakdown and possibly conflict	13.1.1 and 13.1.4
Retaining traditional responses that are no longer appropriate	21.3.2 and 22.4.5.8
Migration may be adaptive or maladaptive or both depending on context and the individuals involved	26.2.1, 26.8.3, 29.3.3, 29.6.2.4

Note: These examples of maladaptation represent a set of cases found in the report that might help the readers to understand the rich range of circumstances in which maladaptive actions might arise. They do not represent a formal categorization of type of maladaptation.

energy source is completed); (2) may lead to higher water costs that will disproportionally affect the poorer households; (3) may divert money and attention from more cost-effective recycling and rainwater harvesting; (4) may reduce incentives to adapt through water conservation approaches; and (5) as a large sunk cost has locked out other options. The plant also affected significant cultural sites of the Bunurong Aboriginal community (Lee and Chung, 2007).

14.6.3. Experiences with Maladaptation

Maladaptation is a cause of increasing concern to adaptation planners, where intervention in one sector could increase vulnerability of another sector or increase the vulnerability of a group to future climate change. An example is the situation experienced by subsistence and smallholder agriculturalists in Palca, Bolivia, who in the face of stressors relating to land access, small holdings, and so forth moved away from their long established practices of diversification of crop varieties and planting locations to more intensive farming practices and cash cropping. They are now seeing evidence of climate change, and the new practices make them more vulnerable to these changes, leading to a risk of insufficient adaptation and maladaptation (McDowell and Hess, 2012). But there can also be tensions between development goals and climate change goals, where people may be aware of a climate related risk but are willing to take that risk (or they may have limited choice) given their current circumstances (IPCC, 2012, Section 4.2.2).

Some studies warn against the simplistic use of maladaptation to communicate the state of high exposure to risks resulting from certain type of livelihoods. For example, the periodic movement of the nomadic pastoralists following the grass and water is a traditional and effective way of dealing with climate variability (Agrawal and Perrin, 2008), but is increasingly being described by some as maladaptive. More focused studies such as Young et al. (2009) put the breakdown of traditional pastoralism in the Sudan into the wider social and political context that led to restrictions on movement, asset stripping, and escalating violence and was undermined by policies not conducive to mobility.

14.7. Research and Data Gaps

A long list of research questions could be identified and prioritized to address gaps and assist the practice of adaptation, and many of these are found in the subsequent adaptation chapters. In this chapter research priorities would range from metrics for adaptation to the psychology of communication about livelihood and life-threatening events. But, the preparation of this report has shown that the practice of adaptation has outstripped the rate at which relevant peer-reviewed research can be produced and disseminated.

Many dedicated researches have become engaged in smaller, often community-based or urban activities where results can be gathered in relatively short time frames and direct interactions between the researchers and the implementers are common. Here research and action can, and are, serving each other and these interactions can be encouraged with support for further cross-community, cross-cultural, and cross-sectoral comparisons.

Effective and timely interaction is more difficult at larger scales. National or multinational programs are often longer and complex and it is difficult to identify the "adaptation" effort within a wider set of policy objectives. Research inputs into decision making too often centers only on better projections of future conditions or *post hoc* assessments of completed projects. The task is made more difficult by relatively short-term research grants, often starting late in the process, or after the process is finished, and by the often rapid turnover of planning and implementation staff, making a close working relationship difficult. But there are models that work. Models based on established and ongoing research teams with a close link to policy such as the EC programs and its formation of targeted research teams across the European Union, CSIR in South Africa, Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the National Climate Change Research Facility (NCCARF) in Australia, the Corps of Engineers and the Regional Integrated Sciences and Assessments (RISAs) in the USA, and UKCIP and its successors in the UK do appear to be more effective in maintaining a dialog with those "on the ground," and this shows in the number of well designed, insightful, and reviewed documents arising from these collaborations.

Unfortunately this model has not been replicated at scale in most developing countries. One might ask why is there only one reference in this volume to any lesson learned from the PPCR – a billion dollar program set up to better understand the challenges of integrating, or mainstreaming, adaptation into development planning with on the ground implementation of many larger than normal adaptation activities? The planning for the PPCR started only in 2008, but the planning process itself is of research relevance, and over the past 2 to 3 years 18 countries have been working through how to bring adaptation into their national planning programs; it is surely a core research interest and opportunity and one whose lifespan already exceeds that of many research projects. Similarly the Adaptation Fund is mentioned only descriptively in these chapters. So where were the groups of independent researchers observing from their point of view, comparing and contrasting countries, and simply conducting the process of independent and collaborative research? The benefit would flow not just from the research itself but also from the interactions with those charged with implementing adaptation and from the challenge to interpret that research so that its implications are relevant to the users, be they government officials or smallholder farmers.

There are models in developing countries. The Consultative Group on International Agricultural Research (CGIAR) network is already making contributions, albeit in the broad domain of agriculture which may be another model. The Coordinated Regional Climate Downscaling Experiment (CORDEX) project will make high-quality high-resolution climate projections available to all countries. The NEPAD Framework for African Agricultural Productivity is another, and there are numerous smaller and effective research efforts too numerous to list here, but few can claim even regional coverage. The Cancun Agreement has already raised the prospect of establishing in a developing country "an international centre to enhance adaptation research and coordination." This may provide the vehicle to tackle some of the problems described above. The UN Agencies, the MDBs, and many bilateral agencies, which are heavy users and sometimes producers of "research," could be major beneficiaries and supporters.

Two points in a review of a decade of experience in the RISA process in the USA stand out. One was an insistence that research team members should primarily be residents in their region of study, and to paraphrase another insight, "knowing what one ought to do is not the same as knowing how to do it" (Pulwarty et al., 2009). In arguing for the establishment of the skills to establish an Australian film industry, Phillip Adams advised the Prime Minister,[8] "It's time to see our own landscapes, hear our own voices and dream our own dreams." Those words could just as well apply to tackling adaptation.

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8 http://www.abc.net.au/dimensions/dimensions_in_time/Transcripts/s796788.htm, accessed 3rd Oct 2013.

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15 Adaptation Planning and Implementation

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Frequently Asked Questions

15.1: What is the present status of climate change adaptation planning and implementation across the globe? 876

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Executive Summary

Adaptation to climate change is transitioning from a phase of awareness to the construction of actual strategies and plans in societies (*robust evidence*, *high agreement*). The combined efforts of a broad range of international organizations, scientific reports, and media coverage have raised awareness of the importance of adaptation to climate change, fostering a growing number of adaptation responses in developed and developing countries. This represents major progress since the IPCC Fourth Assessment Report (AR4). The literature illustrates heterogeneity in adaptation planning related to the context specific nature of adaptation, but also to the differences in resources, values, needs, and perceptions among and within societies. However, it is not yet clear how effective these responses currently are and will be in the future. Few adaptation plans have been monitored and evaluated. There is a tendency in the literature to consider adaptation planning a problem-free process capable of delivering positive outcomes, underestimating the complexity of adaptation as a social process, creating unrealistic expectations in societies, and perhaps overestimating the capacity of planning to deliver the intended outcome of adaptation. {15.2.1-2}

The national level plays a key role in adaptation planning and implementation, while adaptation responses have diverse processes and outcomes at the subnational and local levels (*robust evidence*, *high agreement*). National governments assume a coordinating role of adaptation actions in subnational and local levels of government, including the provision of information and policy frameworks, creating legal frameworks, actions to protect vulnerable groups, and, in some cases, providing financial support to other levels of government. In the increasing number of adaptation responses at the local level in developed and developing countries, local agencies and planners are often confronted by the complexity of adaptation without adequate access to guiding information or data on local vulnerabilities and potential impacts. Even when information is available, they are left with a portfolio of options to prepare for future climatic changes and the potential unanticipated consequences of their decisions. Therefore, linkages with national and subnational levels of government, as well as the collaboration and participation of a broad range of stakeholders, are important. Steps for mainstreaming adaptation have been identified but challenges remain in their operationalization within the current structures or operational cultures of national, subnational, and local agencies. {15.2.1, 15.5.1}

Institutional dimensions in adaptation governance play a key role in promoting the transition from planning to implementation of adaptation (*robust evidence*, *high agreement*). While institutional dimensions may both enable and limit adaptation planning and implementation, the literature has so far mostly reported on how current institutional arrangements restrict the mainstreaming of climate adaptation. The most commonly emphasized barriers or enablers of institutional change in planning and implementation identified for both developing and developed countries are: (1) multilevel institutional coordination between different political and administrative levels in society; (2) key actors, advocates, and champions initiating, mainstreaming, and sustaining momentum for climate adaptation; (3) horizontal interplay between sectors, actors, and policies operating at similar administrative levels; (4) political dimensions in planning and implementation; and (5) coordination between formal governmental, administrative agencies, and private sectors and stakeholders to increase efficiency, representation, and support for climate adaptation measures. {15.2.2, 15.5.1}

Adaptation planning and implementation are dynamic iterative learning processes recognizing the complementary role of adaptation strategies, plans, and actions at different levels (national, subnational, and local) (*robust evidence*, *high agreement*). Climate change adaptation (CCA) takes place as a response to multiple stresses, which highlights the need of connecting CCA with development strategies and plans, and disaster risk management (DRM). The importance of CCA is influenced by how the issue is framed in particular contexts, and, to the extent that it is viewed as a public safety issue or a development issue, it has greater resonance within national and local policies. In many cases, the most attractive adaptation actions are those that offer development benefits in the relatively near term, as well as reductions of vulnerabilities in the longer term. There is a growing recognition in the literature that the linkages between adaptation, development, and DRM need to be more explicit targeting co-benefits among the societal goals. Considering adaptation planning and implementation learning processes can help carrying out periodic adjustments to accommodate changes in climate and socioeconomic conditions that can strengthen the role of planning as a societal tool for CCA and DRM. {15.2.1, 15.3.2-3, 15.5.1}

There is no single approach to adaptation planning because of the complex, diverse, and context-dependent nature of adaptation to climate change. Although top-down and bottom-up approaches are widely recognized, the actions in practice are combinations of these approaches (*medium evidence*, *high agreement*). The literature illustrates that the debate of climate change is dominated at

present by impacts-led approaches that focus on climate risks through the construction of defensive infrastructure rather than on human vulnerability. It is unclear at this point if these adaptation plans consider impact-led approaches just the start of an adaptation process rather than its culmination. Knowledge of impacts and vulnerabilities does not necessarily lead to the most cost-effective and efficient adaptation policy decisions. This is partly due to the uncertainty associated with future climate and socioeconomic conditions but also to the context specificity of adaptation. The literature suggests that coupling adaptive improvements in infrastructure with efforts to improve ecosystem resilience, governance, community welfare, and development improve community resilience. It also suggests combining top-down and bottom-up approaches strengthens adaptation planning and implementation. {15.2.1, 15.3.1, 15.3.3, 15.5.1.2, Box 15-1}

A variety of tools are being employed in adaptation planning and implementation depending on social and management context (*robust evidence*, *high agreement*). Uncertainties in climate change, coupled with the complexities of social-ecological systems, emphasize the need for a variety of tools in adaptation planning and implementation. Information and knowledge on climate change risks from various stakeholders and organizations are essential resources for making adaptation planning. Multidisciplinary efforts have been engaged to develop, assess, and communicate climate information and risk assessments across time scales. These efforts employ a mixed portfolio of measures, from simple agroclimate calendars to computerized decision-support tools. Although a wide range of adaptations are possible with current technologies and management practices, development and diffusion of technologies can expand the range of adaptation possibilities by expanding opportunities or reducing costs. Monitoring and early warning systems play an important role in helping to adjust and revise adaptation implementation, especially on the local scale. Innovative tools have also been developed, such as ecosytem-based adaptation and a range of insurance tools. {15.4}

15.1. Introduction

As impacts of climate change have become apparent around the world, adaptation has attracted increasing attention. The impacts are expected to be particularly severe in the developing world and among marginalized communities because of limited adaptive capacity. Adaptation is an important pillar for the response to climate change, and the IPCC Assessment Reports highlight the complementary roles of mitigation and adaptation in climate policy. Particularly, IPCC Fourth Assessment Report (AR4) (IPCC, 2007) provided an evaluation of adaptation that is the departure point for the present report. The AR4 emphasized that adaptation will be necessary to address impacts resulting from climate change that is already unavoidable due to past emissions. A wide array of adaptation options were noted, but also that the level of adaptation was inadequate for a reduction in vulnerability to future climate change. Moreover, the report showed there are barriers, limits, and costs that are not fully understood.

Since the publication of IPCC AR4, significant progress has been made on the adaptation activities both quantitatively and qualitatively. In particular, there is substantial progress in development of national adaptation strategies and plans. These include climate change adaptation (CCA) legislation and formal national strategies. As of 2012, 26 of the Organisation for Economic Co-operation and Development (OECD) countries have developed or are currently developing strategic frameworks for national adaptation (Mullan et al., 2013). Forty-nine least developed countries produced and submitted National Adaptation Programmes of Action (NAPAs) to the United Nations Framework Convention on Climate Change (UNFCCC) as of 2013. At the same time, the academic literature and reports from multilateral development agencies, international organizations, and non-governmental organizations (NGOs) document numerous cases of community-based activities for CCA in developing countries. Through these activities, a range of lessons are being learned, while barriers and limits are also emerging. The wider social dimensions of adaptation have also attracted more attention since AR4. As the diverse, complex, and context-specific nature of adaptation becomes apparent (differences in resources, values, needs, and perceptions among and within societies), the related areas expand in the wider social-ecological system, and the number of stakeholders increases. Based on this recognition, the importance of mainstreaming adaptation and the integration of adaptation policies within those of development increases.

Current research has expanded its focus to reflect these advances (Biesbroek et al., 2010). Until the mid-1990s, research on climate change focused almost exclusively on understanding of climate system dynamics and modeling of future climate. Several programs developed recently give prominence to studies of vulnerability and adaptive capacity, and associated adaptation options, measures, and strategies, including local, regional, and sectoral studies. As adaptation activities progress, many challenges have emerged, such as how to manage the decision-making process, how to develop strategies and plans, and how to implement them. In this regard, the roles within multilevel governance become an issue, such as horizontal coordination among different agencies and departments, and vertical coordination of various stakeholders from regional, national, to local actors. Furthermore, many countries face challenges in moving from the development of adaptation strategies and plans to implementation. These provide challenges for the research community as well.

There are many definitions and characteristics of adaptation strategies (Carter et al., 1994; Burton et al., 2005). For the purpose of this chapter, adaptation strategies are defined as a general plan of action for addressing the impacts of climate change, including climate variability and extremes. Such strategies include a mix of policies and measures that have the overarching objective of reducing vulnerability to climate change impacts. This chapter examines and evaluates the literature on CCA, in order to assess the progress made toward CCA and explore difficulties encountered in the implementation of adaptation plans. The IPCC Working Group II (WGII) Fifth Assessment Report (AR5) has four interrelated chapters about adaptation that discuss complementary aspects of the process (see Figure 14-1). This chapter focuses on the actions taken from international to local levels, in various sectors in order to assess (1) the recent status of CCA planning and implementation across the globe; (2) the characteristics of adaptation in different settings; (3) the strategies, approaches, and tools used in the adaptation practices; and (4) the governance of adaptation including building adaptive capacities. This chapter also draws attention to factors that motivate and facilitate the development of adaptation strategies, as well as how scientific and technical information, support, and collaborative mechanisms are utilized in the process.

15.2. Status of Adaptation Planning and Implementation

15.2.1. Adaptation Planning at Different Levels

15.2.1.1. Common Recognition and International Mechanisms

The combined efforts of a broad range of international organizations, scientific reports, and media coverage have raised awareness of the importance of adaptation to climate change since the publication of AR4. Adaptation is transitioning from a phase of awareness and promotion to the construction and implementation of plans, strategies, legislation, and projects at national, subnational, and local levels (Biesbroek et al., 2009; Preston et al., 2009; Tompkins et al., 2010; Berrang-Ford et al., 2011; Romero-Lankao and Dodman, 2011; Dodman, 2012). The review of the literature identifies a high heterogeneity of adaptation planning. There is significant heterogeneity in adaptation planning that is related to the context-specific nature of adaptation (differences in resources, values, needs, and perceptions among and within societies). This heterogeneity also results from different approaches among countries, multilateral development agencies, and international organizations that promote and fund adaptation, and from differences in knowledge, information, and awareness on adaptation alternatives across societies.

Although attention to climate change impacts and disaster risk management are key elements of adaptation, they appear to have a more prominent role in the early stages of planning and implementation (Few et al., 2007a; Hofstede, 2008; Mitchell et al., 2010; Garrelts and Lange, 2011; Harries and Penning-Rowsell, 2011; Rosenzweig et al., 2011; Rumbach and Kudva, 2011; Etkin et al., 2012; IPCC, 2012). Several authors express concern that a strong focus on impacts can overshadow the analysis of the underlying stressors of hazards, neglecting the drivers of vulnerability, and thus limiting the effectiveness for interventions (Sabates-Wheeler et al., 2008; Boyd and Juhola, 2009; Orlove, 2009; Ribot, 2010; Rumbach and Kudva, 2011). This approach could obscure opportunities for connecting development pressures, poverty, social inequality, and climate change, particularly for the reduction of social vulnerability (Lemos et al., 2007; Hardee and Mutunga, 2010; Sietz et al., 2011). Furthermore, other scholars suggest that knowledge of impacts and vulnerabilities does not necessarily lead to the most cost-effective and efficient adaptation policy decisions (Hulme et al., 2009; Barnett and Campbell, 2010).

The importance of climate adaptation is also influenced by how the issue is framed. For example, to the extent that adaptation is viewed as a development issue (current development stressors and challenges; existing policy and existing agendas; and knowledge, risks, and issues communities already face), it may have greater resonance within local government (Ewing et al., 2008; Moser and Satterthwaite, 2008; Dovers, 2009; Hodson and Marvin, 2009; Stringer et al., 2009; Measham et al., 2010; Sanchez-Rodriguez, 2012). Multilateral development agencies encourage efforts in this direction through a number of guidelines, publication, and development assistance (UNDP, 2004; USAID, 2007; OECD, 2009; World Bank, 2010; UN-HABITAT, 2011a). Central to these efforts is the role of planning that connects adaptation to development needs and challenges (Blanco and Alberti, 2009; Dovers, 2009; Juhola and Westerhoff, 2011; Sanchez-Rodriguez, 2012). A critical issue commonly emphasized in the literature is the consideration of adaptation planning as a problem-free process capable of delivering positive outcomes. There is the risk of underestimating the complexity of adaptation planning as a social process, and it can lead to creating unrealistic expectations in societies, and overestimating the capacity of planning to deliver the intended outcome of preparing societies to adapt to the negative impacts of climate change. This highlights the importance of monitoring, evaluating, and reviewing adaptation planning and implementation (Adger et al., 2009b; Preston et al., 2009; Tompkins et al., 2010; Wolf et al., 2010).

The fast growth of international mechanisms for supporting adaptation planning has assisted in the creation of adaptation strategies, plans, and actions at the national, subnational, and local level. The directives and initiatives of the European Commission (EC) have fostered the creation of a large number of national adaptation strategies and plans in EU member countries since the last IPCC report (Biesbroek et al., 2009, 2010; Ford et al., 2011). Other relevant regional initiatives are the South Pacific Regional Environmental Programme (SPREP) supported by a number of international agencies, and in the Caribbean through the Caribbean Catastrophic Risk Insurance Facility (Pulwarty et al., 2010). The literature reports a growing number of mechanisms developed by multilateral development organizations, development cooperation agencies from developed countries, United Nations programs (UNDP, 2004, 2010a; UN-HABITAT, 2010, 2011a), multilateral development agencies (USAID, 2007; OECD, 2009; World Bank, 2010, 2011a; Abbas et al., 2012), and NGOs (ICLEI, 2008; IFRC et al., 2009; Pew Centre on Global Climate Change, 2009; Braman et al., 2010; ActionAid et al., 2012; Crane, 2013). These organizations focus on their particular geographic and thematic areas of interest in their support for adaptation planning. Particularly relevant are the activities of UNFCCC for least developed countries (LDCs) through the National Adaptation Programmes of Action (NAPAs) and for LDCs and other developing countries through the National Adaptation Plans (NAPs).

Key funding mechanisms are associated with the Global Environmental Facility (GEF) adaptation funds (Least Developed Countries Climate Adaptation Fund and Special Climate Change Fund), support for the Pilot Program for Climate Resilience (PPCR), and special purpose adaptation funds for UN agencies. The Adaptation Fund (AF) set up under the Kyoto Protocol has pioneered direct access mechanisms to developing countries, allowing countries to access essential funds without having to work through a multilateral development agency.

15.2.1.2. National Initiatives

The movement to introduce adaptation into national policies has accelerated in both developed and developing countries. These diverse national adaptation initiatives reflect the characteristics of the domestic political structures, socioeconomic conditions, values, and perceptions, as well as development stresses and opportunities. National governments are assuming a coordinating role in adaptation actions in subnational and local levels of government. National-level coordination includes the provision of information about potential risks, in order to strengthen actions of state and local governments. These activities provide policy frameworks that guide decisions at subnational levels, to spur and coordinate the creation of legal frameworks, to direct action in sectors and resources for national development (agriculture, fisheries, health, ecosystem protection, among others), to protect vulnerable groups, and to provide financial support to other levels of government (Hulme et al., 2009; Biesbrock et al., 2010; Birkmann and Teichman, 2010; Berrang-Ford et al., 2011; Westerhoff et al., 2011). National governments also facilitate the coordination of budgets and financing mechanisms (Alam et al., 2011; Kalame et al., 2011).

In recent years, Europe's creation of national adaptation strategies and plans has been particularly dynamic. Twelve European countries have created National Adaptation Strategies: Austria, Belgium, Denmark, Finland, France, Germany, Hungary, the Netherlands, Norway, Portugal, Spain, and UK (only two of them were created before the AR4—Finland and Spain) (Biesbroek et al., 2010). Moreover, some countries have programmed the evaluation of their national adaptation strategies because they recognize the need to learn from the adaptation process (UK, Germany, Australia, the USA, and Mexico, among others) (Bierbaum et al., 2013). Most strategies are regarded as the start of a policy process rather than its culmination, providing the important perspective of considering iterative evaluation as part of planning and implementation (Hulme et al., 2009; Biesbroek et al., 2011; Pulwarty et al., 2012).

The LDCs national adaptation responses—implemented through UNFCCC's NAPAs—provide data on efforts to link local level adaptation and development (Agrawal, 2008; Agrawal and Perrin, 2008; Stringer et al., 2009). More than 50% of the projects under this program are concentrated in three key sectors for development and livelihoods: food security, terrestrial ecosystems, and water resources. They attract the support of a greater range of actors, but some suggest that linkages between development and adaptation need to be made more explicit

(Stringer et al., 2009). Sustained monitoring, evaluation, and feedback that is needed to learn from the NAPAs process would help these countries transcend from a project-by-project effort to a more complete union of adaptation and domestic and local development. Assessment on NAPAs is also given in Section 14.4.4.

15.2.1.3. Subnational and Local Activities

Adaptation planning and implementation initiatives illustrate differences on the role of subnational governments in the governance structure of countries, from those with strong concentration of political and economic power to a very minor role in governance and decision making. Subnational governments often have a complementary role to national governments in adaptation planning that is reflective of the governance structure (Moser, 2005; West and Gawith, 2005; Lemmen et al., 2008; Karl et al., 2009; Pew Centre on Global Climate Change, 2009). Although guiding frameworks have not created for subnational governments in many countries, the states and provinces in some countries have an active role in CCA (Brekke et al., 2009; Dinse et al., 2009; Staples, 2011; Barsugli et al., 2012; Bierbaum et al., 2013; Mukheibir et al., 2013).

There is a significant increase in the number of planned adaptation responses at the local level in rural and urban communities of developed and developing countries since AR4. Climate adaptation is context dependent and it is uniquely linked to location, making it predominantly a local government and community level of action (Corfee-Morlot et al., 2009; Glaas et al., 2010; Mukheibir et al., 2013). Among these efforts are adaptation plans that utilize local knowledge. Local knowledge-based adaptation is focused primarily on the use of traditional knowledge to increase adaptive capacity at the community level, examples of which are shown in Table 15-1. In addition to raising adaptive capacity, local

Table 15-1 | Application of local knowledge in climate change adaptation.

Location	Sector	Approach and strategy	Adaptive action implemented	Institutions	References
Southern Kimberley, Australia	Water supplies	• Define vulnerabilities • Increase adaptive capacity	• Compile observed changes • Increase monitoring • Manage water resources • Review TEK[a]	Universities; NGOs;[b] United Nations University	Green et al. (2010); Prober et al. (2011); Leonard et al. (2013)
Trinidad, Bolivia and northern central Bolivia	Ecosystems, agriculture	Reduce vulnerability	• Revive "camellones" (earthen platforms) TEK • Reduce erosion • Document local observations	Oxfam International; NGOs; Bolivian government; Food and Agriculture Organization	Oxfam International (2009)
Pinoleville Pomo Nation (California, USA)	Infrastructure	• Mitigation: solar power • Increase adaptive capacity	• Co-design infrastructure • Address insufficient capital • Address water shortages and energy needs	Universities; NGOs; Housing and Urban Development	Shelby et al. (2012); Pinoleville Pomo Nation Housing flyer (2013); Redsteer et al. (2013)
Fiji	Ecosystems and water supply	• Define vulnerabilities • Increase adaptive capacity	• Recognize TEK • Enable adaptive decision making • Enhance community awareness • Participate in development	Australian Agency for International Development; Fiji Department of Environment; University of the South Pacific	Dumaru (2010)
Kenya, Tanzania, Malawi, Zimbabwe, southern Zambia	Agriculture	• Define vulnerabilities • Increase technical capacity • Increase adaptive capacity	• Use drought early warning • Apply TEK • Develop novel reporting • Compile observed changes • Harvest rainwater • Change tilling practices • Use appropriate crop varieties	University of Capetown; University of Nairobi; the United Kingdom's Department for International Development; Canada's International Development Research Centre	Chang'a et al. (2010); Mugabe et al. (2010); Kalanda-Joshua et al. (2011); Majule et al. (2013); Masindel et al. (2013)
Reservation lands (western USA)	Health, water supplies, environment	• Define vulnerabilities and impacts • Increase adaptive capacity	• Compile observed changes • Utilize environmental legislation • Review indigenous knowledge • Analyze local meteorological data • Analyze historical/legal context • Increase monitoring	Universities and affiliated NGOs; tribal offices; federal agency research	Redsteer et al. (2010); Doyle et al. (2013); Gautam et al. (2013)

[a]TEK = Traditional ecological knowledge: adaptive ecological knowledge developed through an intimate reciprocal relationship between a group of people and a particular place over time.

[b]NGO = Nongovernmental organization.

Frequently Asked Questions

FAQ 15.1 | What is the present status of climate change adaptation planning and implementation across the globe?

Climate change adaptation has been receiving increasing attention as a result of recent media coverage and reports. Since the publication of the IPCC Fourth Assessment Report (AR4), a large assortment of adaptive actions has taken place in response to observed climate impacts. These actions mostly address sectoral interests, such as agricultural practices (e.g., altering sowing times, crop cultivars and species, and irrigation and fertilizer control), public health measures for heat-related risks (e.g., early warning systems and air pollution control), disaster risk reduction (e.g., early warning systems), and water resources (e.g., supply and demand management). Some of these are "autonomous" actions in a specific sector.

Another area where progress has been made since AR4 is the development of broad national-level plans and adaptation strategies. These have now been established in developed and developing countries worldwide. Because adaptation policy requires decision making amid uncertainties about future climate change and its impacts, the major pillars of adaptation plans are iterative assessment, flexible and adaptive planning, and enhancement of adaptive capacity. Adaptation plans are being developed and documented at the national, subnational, and community levels and by the private sector; however, there is still limited evidence of adaptation implementation. Implementation remains challenging because in the transition from planning to implementation the many interested parties must overcome resource, institutional, and capacity barriers. The difference in time scales between medium- and long-term adaptation plans and pressing short-term issues poses a significant problem for prioritizing adaptation.

In parallel with national-level planning, community-based adaptation (CBA) has become an increasingly prevalent practice, particularly in developing counties. It is increasingly apparent that CBA potentially offers ways to address the vulnerability of local communities by connecting climate change adaptation to non-climate local needs. Cities and local governments have also begun active engagement in climate change adaptation. Local governments play an important role in adaptation because they directly communicate with affected communities. For the past several years, leading practices have begun in New York City, Mexico City, Toronto, Albay Province in the Philippines, and elsewhere. These achievements were possible because of elected and local leadership; cooperation among national and local governments, private sectors, and communities; and the participation of boundary organizations, scientists, and experts.

knowledge often highlights vulnerabilities and impacts that may not be well known, especially when the areas where local knowledge is still held are remote and poorly monitored (e.g., Majule et al., 2013).

Indigenous communities are those populations that have cultural and historical ties to specific homelands. They are generally distinct from politically dominant populations (Battiste, 2008). Because of these characteristics, they are particularly vulnerable to climate change impacts. When assessing indigenous vulnerability and developing CCA strategies and resilience to climate change, the following issues need to be examined and addressed: the relationship of indigenous peoples to land, the degree of migration or displacement of indigenous communities (Miron, 2008), and their adaptive capacity. Vulnerability and challenges to adaptation for indigenous people are discussed broadly in Chapters 13, 27, and 28.

Local councils and planners are often confronted by the complexity of adaptation without adequate access to guiding information or data on local vulnerabilities and potential impacts. Even when information is available, they are left with a portfolio of options to prepare for future climatic changes but without effective guidance on decision making and the potential for unanticipated consequences arising from those decisions (Wilson, 2006; Storbjörk, 2007; Patt and Schröter, 2008; Urwin and Jordan, 2008; Gupta et al., 2010; Mathew et al., 2012; Rodima-Taylor et al., 2012; Mukheibir et al., 2013).

Local governments play a central role addressing the challenges of adaptation planning and implementation (Blanco and Alberti, 2009; Sanchez-Rodriguez, 2009; Rosenzweig and Solecki, 2010; Simon, 2010; Matthews, 2012). However, scholars stress the important role of partnerships among public, civic, and private sectors in CCA (Berkhout et al., 2006; Agrawal, 2010; Tompkins et al., 2010; Howe, 2011; Tompkins and Eakin, 2012). Inclusive and participatory approaches in adaptation planning at the local level are encouraged by international organizations (UNDP, 2004, 2010a; Moser, 2008; Moser and Satterthwaite, 2008; Ensor and Berger, 2009; Geiser and Rist, 2009; World Bank, 2010; Ford et al., 2011; UN-HABITAT, 2011a).

Urban areas are also the locus of a growing number of planning initiatives (Revi, 2008; Roberts, 2008; Stren, 2008; Blanco and Alberti, 2009; Hamin and Gurran, 2009; Hardoy and Pandiella, 2009; Lowe et al., 2009; O'Demsey, 2009; Parzen, 2009; Sanchez-Rodriguez, 2009; Tanner et al., 2009; Corfee et al., 2010; Rosenzweig and Solecki, 2010; Simon, 2010; City of New York, 2011; City of Rotterdam, 2011; Romero-Lankao and Dodman, 2011; Rosenzweig et al., 2011; Carmin et al., 2012; Matthews, 2012). The primary determinant in creating adaptation plans has been a response to current climate extremes as well as potential future impacts (Rosenzweig and Solecki, 2010; Rosenzweig et al., 2011; Carmin et al., 2012). The difference in approaches has implications for adaptation governance, institutional arrangements, resources, and stakeholders' involvement in the planning and implementation processes. Understanding how these approaches work merits further analysis. Enforcing parallel agendas for DRM and CCA runs the risk of duplicating efforts and resources, creating competing actions and potential conflicts with unintended negative consequences, including maladaptation. Institutional arrangements would need to bridge the divide between CCA and DRM, particularly in terms of legislation, operational and management structures, working agendas, and time horizons (Schipper and Pelling, 2006; Birkmann and Teichman, 2010; Falaleeva et al., 2011).

15.2.2. Adaptation Implementation

There is a minority of academic literature that provides information on the implementation of adaptation plans, in contrast with the large accumulation of literature that discusses concepts, strategies, and plans of adaptation. Projects and cases of adaptation, including those implemented, are presented mainly in reports from international organizations, multilateral development organizations, national and subnational governments, and NGOs (e.g., UNFCCC, 2011; Mullan, 2013). In addition, the sectoral and regional chapters in this report have segments that discuss adaptation planning and implementation and that provide an additional database of sectors and practices. Therefore, this section assesses the status of adaptation implementation based on these chapters in addition to other literature.

Adaptation practices reflected in the WGII AR5 include agriculture, public health for heat-related risks, disaster risk reduction, water resources, coasts, and urban areas, among others. Options and approaches used in implementation vary widely, ranging from traditional and existing to new and innovative measures. For example, farmers have been adapting to climate change worldwide, and current common practices include altering sowing times, crop cultivars and species, or irrigation and fertilizer control (Fujisawa and Koyabashi, 2010; Lasco et al., 2011; Olesen et al., 2011); reduced tillage practices; and technical measures to more effectively capture rainwater and reduce soil erosion (Thomas et al., 2007; Marongwe et al., 2011; see also Sections 7.5.1, 22.4.5.7, 23.4.1, 24.4.4.5, 27.3.4.2). These have proven to be effective in many cases, while some measures faced other problems; for example, earlier sowing is often prevented by lack of soil workability and frost-induced soil crumbling (Oort, 2012). Furthermore, simple options such as changes in sowing and harvesting dates may become less successful in a more variable climate (Moriondo et al., 2010; see also Section 23.4.1). Adaptation in agriculture is also linked with water management. Adaptation to water scarcity can be improved by taking into account a set of agronomic practices and irrigation such as deficit irrigation (Geerts and Raes, 2009; see also Section 27.3.4.2). For public health for heat-related risks, major approaches are developing early warning systems and air pollution control. According to Chapter 11 on Human Health, some studies report that heat wave early warning systems are effective to reduce heat-related mortality, resulting in fewer deaths during heat waves after implementation of the system (e.g., Ebi et al., 2004; Tan et al., 2007; Fouillet et al., 2008). A national assessment attributed the lower death toll to greater public awareness of the health risks of heat, improved health care facilities, and the introduction in 2004 of a heat wave early warning system (Fouillet et al., 2008; see also Section 11.7.3).

Mullan (2013) indicated that implementation of adaptation plans are still at an early stage despite the rapid development of strategies and plans that have occurred in OECD countries. In many sectors, adaptation to both environmental conditions and climate change includes accumulating traditional experience and knowledge for adaptation. Furthermore, each country has also developed its own policies and options to prevent, cope with, mitigate, and utilize various environmental changes. As the occurring adaptive actions are usually based on such existing knowledge and options, they are incremental. Research has shown that local governments that have started implementing adaptation plans mostly tend to adopt a reactive or event-driven approach to adaptation relying on technical measures. Often the focus is on climate variability and current weather extremes rather than long-term climate change (Næss et al., 2005; Tompkins, 2005; Wall and Marzall, 2006; Crabbé and Robin, 2006; Storbjörk, 2007; Blanco and Alberti, 2009; Amundsen et al., 2010; Glaas et al., 2010; Anguelovsky and Carmin, 2011; Measham et al., 2011; Preston et al., 2011; Dannevig et al., 2012; Romero-Lankao et al., 2012; Runhaar et al., 2012). Climate adaptation efforts reported on at present are often piecemeal and fragmented approaches, dealing with partial solutions and approaches to climate adaptation, rather than more full-scale implementation (Granberg and Elander, 2007; Blanco and Alberti, 2009; Bulkeley et al., 2009; Amundsen et al., 2010; Burch, 2010; Tompkins et al., 2010; Preston et al., 2011; Dannevig et al., 2012; Mees et al., 2012; Romero-Lankao, 2012; Runhaar et al., 2012). In many cases, these practices have been embedded in existing policies, and thus not necessarily framed or made visible as climate adaptation actions (Tompkins et al., 2010; Berrang-Ford et al., 2011; see Box 25-5). It should be noted that several of these reports on local climate adaptation actions have been taking place without explicit regulative demands for climate adaptation.

A particular challenge is implementation of local and short-term decisions in the context of long-term climate information. Improving the use of climate risk information across time scales, especially in the context of early warning systems, has helped bridge these gaps (van Aalst, 2009; IPCC, 2012; Pulwarty and Verdin, 2013). Independent from the growing attention for extremes in CCA, there has also been a shift in disaster risk management policy and practice, aiming to shift the balance of attention and expenditure from disaster response and reconstruction to disaster risk reduction and building resilience (not limited to climate-related extreme events).

There is growing awareness of the need for ecosystem-based, institutional, and social measures, although engineered and technological adaptation options are the most common adaptive responses (see Box CC-EA). A feature captured in WGII AR5 is that integrated approaches have been pursued in many areas such as integrated water resource management and integrated coastal management (see Table 3-3; Sections 8.3.3.4 and 23.7.2 for water; Section 5.5.4 for coasts). These integrated policies aim at addressing multiple objectives including CCA, development, and disaster risk reduction. For example, the U.S. Water Utilities Climate Alliance (WUCA, 2010) provides a comprehensive overview of ways of delivering water management which incorporates climate change and its uncertainty. Climate change has been incorporated into water resources planning in England and Wales (Arnell, 2011; Wade et al., 2013) and in the Netherlands (de Graaff et al., 2009). Guidance has been also developed on the inclusion of adaptation in water management (UNECE, 2009) and river basin management plans (EC, 2009b; see also Section 23.7.2). Many sectors promote adaptive management in CCA to improve flexibility in its implementation.

Targets of early adaptation are focused on capacity building within governments and communities. These important first steps include increasing awareness of the risk of climate change, access to scientific information, development of common goals, and creation of operational institutions, which are important premises for adaptation. Capacity building itself is often a target of adaptation implementation, particularly in developing countries (e.g., van Aalst et al., 2008; Simões et al., 2010; UNFCCC, 2013; see Table 15-1 for capacity building cases). There are many factors to promote or hinder the implementation of adaptation; Table 15-2 provides examples where the drivers and motivations for transition to implementation are highlighted. Section 15.5 provides an analysis of the role of institutional dimensions for both planning and implementation of adaptation.

15.2.3. Financing for Adaptation

Adapting to the impacts of climate change requires the mobilization of a significant amount of funding for adaptation measures in a wide range of sectors. A number of studies suggest that the annual amount of adaptation funding needed by developing countries by 2030 is on the order of several tens of billions of dollars (e.g., UNFCCC, 2007;

Frequently Asked Questions

FAQ 15.2 | What types of approaches are being used in adaptation planning and implementation?

Adaptations employ a diverse portfolio of planning and practices that combine subsets of:

- Infrastructure and asset development
- Technological process optimization
- Institutional and behavioral change or reinforcement
- Integrated natural resources management (such as for watersheds and coastal zones)
- Financial services, including risk transfer
- Information systems to support early warning and proactive planning.

Although approaches vary according to context and the level of government, there are two general approaches observed in adaptation planning and implementation to date: top-down and bottom-up. Top-down approaches are scenario-driven and consist of localizing climate projections, impact and vulnerability assessments, and formulation of strategies and options. National governments often take this approach. National adaptation strategies are increasingly integrated with other policies, such as disaster risk management. These tendencies lead to adaptation mainstreaming, although there are various institutional barriers to this process. As the consideration of the social dimensions of climate change adaptation has attracted more attention, there has been an increased emphasis on addressing the needs of the groups most vulnerable to climate change, such as children, the elderly, disabled, and poor. Bottom-up approaches are needs driven and include approaches such as community-based adaptation (CBA). CBA is often prominent in developing countries, but communities in developed countries also use this approach. Where a combination of top-down and bottom-up activities has been undertaken, the links between adaptation planning and implementation have been strengthened. In either approach, participation by a broad spectrum of stakeholders and close collaboration between research and management have been emphasized as important mechanisms to undertake and inform adaptation planning and implementation.

Local governments and actors may face difficulties in identifying the most suitable and efficient approaches because of the diversity of possible approaches, from infrastructure development to "softer" approaches such as integrated watershed and coastal zone management. National and subnational governments play coordinating roles in providing support and developing standards and implementation guidance. Therefore, multilevel institutional coordination between different political and administrative levels is a crucial mechanism for promoting adaptation planning and implementation.

Table 15-2 | Transition from planning to implementation.

Scale	What is being implemented and why	Transition from planning to implementation	Monitoring and evaluation
Village of Kaslo (British Columbia) and surrounding unincorporated rural areas (Regional District of Central Kootenay (RDCK) Electoral Area D). Implemented 2010–2012. (Kaslo and Regional District of Central Kootenay Partnership, 2010)	The Village of Kaslo and RDCK Electoral Area D developed a Climate Adaptation Action Plan and identified water supply as a key community vulnerability related to projected climate change. Action plan noted that current demand for water almost equaled supply and observed the very limited data on water supply for creeks that supply water for the community.	The Village of Kaslo and RDCK Electoral Area D brought in experts in fields related to climate change impacts and involved extensive public outreach and engagement. Adaptation planning process identified projected changes in stream freshet and stream flows associated with climate change could result in insufficient water supply. Community leaders working through the Kaslo and District Community Forest Society sought funds to establish stream flow monitoring stations and developed a monitoring framework on key creeks to track changes in flows providing water to communities within Kaslo and RDCK Area. The Columbia Basin Trust contributed funding to this effort as part of follow-up to its support of the initial climate change planning process.	Monitoring and evaluation performed by Columbia Basin Trust's Communities Adapting to Climate Change Initiative. Electoral Area D Advisory Planning Commission monitors the implementation of action recommendations.
National Framework on Local Adaptation Plans for Action (LAPAs), Nepal. Implementation began in 2011. (Government of Nepal, 2011)	Nepal adopted the LAPA in 2011, becoming the first country to promote a bottom-up approach to adaptation planning and implementation. The National Adaptation Plan for Action and the National Climate Change Policy state that at least 80% of the available budget will go toward directly implementing adaptation actions at the local level. To date, 70 LAPAs have been prepared (69 at the village administrative scale and 1 within a municipality) and are under implementation by vulnerable communities.	Policy makers recognized the need to integrate local and context specific adaptation plans into local to national adaptation planning as a way to ensure robust climate change adaptation planning and implementation. The Ministry of Science, Technology and Environment and the Ministry of Federal Affairs and Local Development played a leadership role at the central level in coordinating the development and implementation of LAPAs.	Monitoring and evaluation play key roles in supporting iterative planning. Financial arrangements play a key role in integrating local adaptation options into development planning processes. Adaptation investments are being costed and integrated into annual and medium-term budget frameworks and resource mobilization strategies. Nepal's budget for fiscal year 2013/14 has included Climate Change Financing Code, and of the total budget, 5.36% is directly related to climate change financing.
Local government, the Albay Province, Philippines. Implementation began in 2008. (Lasco et al., 2009)	The Albay Declaration on Climate Change Adaptation specified mainstreaming climate change into local and national development policies. The Albay Integrated Agricultural Rehabilitation Program established farm clusters to assist farmers and fisher folk in their agricultural, food, technological, and training needs.	Program planning began in December 2006 after Typhoon Reming's devastation. The plan prevents scarcity of agricultural commodities, accelerates food production, pump-primes the agricultural industry in the province, and speeds up rehabilitation of upland agricultural areas in Albay. The provincial government of Albay established the Center for Initiatives and Research on Climate Adaptation in 2008, a living research and training institution in collaboration with the Environment Management Bureau, World Agroforestry Centre, Bicol University, and the University of the Philippines Los Baños. Local champions such as the Governor committed time and resources to put climate change on the provincial agenda and also on the national development and policy agenda, addressing the needs of farmers and fisher folk.	Main mechanism for institutional and stakeholder collaboration is through the Inter-Agency Committee on Climate Change Philippine Senate Resolution No. 191, passed during 14th Congress, 1st regular session, adopting the Albay Declaration on Climate Change Adaptation as a framework. Mainstreaming of global warming concerns gives a voice to the Albay Declaration in Congress and directly encourages policymakers to mainstream climate change in policymaking; and indicators measure a cleaner environment for the community, improvement of infrastructure development plans, land development/conversion activities, institutionalization of pre-planning, enhanced implementation, and enhanced monitoring and evaluation.
Pilot Program on Climate Resilience (PPCR), 2009. (CIF, 2012; PPCR, 2013)	Phase I (planning): supported by multilateral development bank partners, in 2 years a strategic plan was developed consistent with national development objectives. Phase II (implementation): countries define "transformational change" in the context of their national circumstances. Scaling up potential of successful pilots (e.g., use of good practices in Bangladesh). Addressing basic needs (e.g., food security in Niger). Mobilization of large-scale resources for investments (e.g., coastal highways in Samoa). Country leadership capacity dependent on experience with integrating climate change into planning activities, institutional and human capacities, and need to respond to emergencies. Recent climate extreme related disasters have affected development.	The capacity of countries to take on a leadership role depended on their prior experience with integrating climate change considerations into planning activities, their institutional and human capacities, and their demands to respond to other emergencies. The strategic plans drew on National Adaptation Plans for Action, national climate change strategies (if they existed), and national development strategies and plans. Lead agency roles assigned to planning or finance ministries (e.g., Zambia, Samoa) or environment-related ministries (e.g., Bangladesh). Disaster risk management units included. Coordinate the work of donors and/or leverage non-PPCR resources. For example, Cambodia and Zambia have leveraged co-financing from the International Fund for Agricultural Development and the Nordic Development Fund, respectively.	The framework includes five core indicators designed to measure outcomes at the country level, aggregated from individual PPCR components. These are (1) number of people supported by the PPCR to manage the effects of climate change; (2) degree of integration of climate change in national, including sector, planning; (3) extent to which vulnerable households, communities, businesses, and public sector services use improved PPCR-supported tools, instruments, strategies, and activities to respond to climate vulnerability and climate change; (4) evidence of strengthened government capacity and coordination mechanisms to mainstream climate resilience; and (5) quality of and extent to which climate-responsive instruments/investment models are developed and tested. All of the core indicators address gender issues either directly or indirectly.

Continued next page →

Table 15-2 (continued)

Scale	What is being implemented and why	Transition from planning to implementation	Monitoring and evaluation
United Kingdom National Adaptation Programme. Implemented in 2012. (UK HM Government, 2013)	Pursuant to the Climate Change Act 2008, the Climate Change Risk Assessment (CCRA) 2012 for the UK brought together the best available evidence, using a consistent framework to identify the risks and opportunities related to climate change. The assessment distilled approximately 700 potential risks down to more than 100 for detailed review. Recent extreme weather in Britain, such as the flooding in the winter of 2012 and the drought of early 2012, brought into sharp relief the importance of anticipating and managing weather extremes. Costs of rebuilding and impacts on essential public services highlighted the need for implementing preparedness and adaptation.	The Climate Ready Support Service provides direct support and online information to help organizations assess their sensitivity to a changing climate and take steps to manage their climate risks. Through the Service the Environment Agency is working with partners in priority sectors to provide tailored tools, guidance, and training to enable them to understand and respond to the challenges of a changing climate. Established partnerships are with the Met Office, the Local Government Association, Climate UK, and the Climate Change Partnerships. The government is also supporting the building of networks of organizations that may share common risks, e.g., the Infrastructure Operators Adaptation Forum.	Progress indicators provide iterative measures of progress to develop the next CCRA: • Process-based markers, such as whether planned policies have been implemented; • Quantitative data, such as statistics on trends in factors that influence risks from flooding and water scarcity. These provide a strong foundation for assessing overall adaptation in relevant areas. Discussions about the most appropriate framework are continuing. The Adaptation Sub-Committee of the Committee on Climate Change under the Climate Change Act assesses progress toward implementation of objectives, proposals, and policies highlighted in this report and the Register of Actions, with assessments published in 2015 and every 2 years hence.

World Bank, 2010; Smith et al., 2013). However, the annual costs could potentially range into the hundreds of billions of dollars (Parry et al., 2009). The differences between these estimates highlight the high degree of uncertainty in how they are derived. Key factors that contribute to this uncertainty include differences in the sets of sectors that are included in the analyses and the analytical methodologies used; uncertainties related to future climate changes and how best to adapt to them; and the lack of an agreed on operational definition of adaptation (e.g., Fankhauser and Burton, 2011; Christiansen et al., 2012; Naidoo et al., 2012; Smith et al., 2013).

Adaptation financing broadly refers to resources that are deployed to support climate-resilient development (World Bank Group, 2011). Funding for adaptation can be mobilized through a range of international and domestic, public and private financing mechanisms, and can take various forms (e.g., loans and grants). Public financing sources are typically used to support projects in the infrastructure sectors, where returns on investments (ROIs) are usually less attractive to private investors. Sources of public financing for adaptation include contributions from national budgets, multilateral and bilateral development funds, and UNFCCC operational funds—the Adaptation Fund, the Least Developed Countries Fund, and the Special Climate Change Fund (Christiansen et al., 2012; Haites and Mwape, 2013; Romani and Stern, 2013). A potentially key source of future public financing for adaptation is the Green Climate Fund that was officially designated at the 17th Conference of the Parties to the UNFCCC in Durban, but is not yet operational.

Examples of ongoing work targeting challenges in priority adaptation themes in several countries are provided by the Climate Change and Water Resources program at the Inter-American Development Bank. The lessons learned from emerging adaptation experiences are, first, that infrastructure investments (e.g., dams, levees, canals) remain critical for climate adaptation and reducing vulnerability to climate and weather-related events; and, second, that infrastructure investments need to be complemented by previously neglected investments in soft infrastructure (e.g., watershed management, land use planning and information, and stakeholder engagement). Efforts are also being supported by other regional development banks; for example, the Climate Adaptation for Rural Livelihoods and Agriculture (CARLA) project is supported by the African Development Bank Group).

Adaptation measures that offer reasonably predictable ROIs that are comparable to the returns on investments for non-adaptation measures with similar risk profiles have more opportunities to receive private financing (Christiansen et al., 2012). The fisheries and agriculture sectors, where operations are often locally owned, are examples of sectors that typically draw relatively high proportions of private financing in developing countries (often from domestic sources). Sources of private financing for adaptation traditionally include a range of financial institutions, such as international banks, multinational corporations, private equity and pension funds, insurance companies, and sovereign wealth funds. Charitable foundations and social investors are also sources of private financing for adaptation; compared to the financial institutions, these sources are often more motivated to provide financing for measures that generate lower ROIs (Christiansen et al., 2012).

Private financing for adaptation is primarily of two types: debt and equity. Debt-based financing typically consists of loans (e.g., bank loans) or bonds that must be paid back over time with interest. Equity-based financing generally involves a transfer of ownership rights through stocks or other assets. Export credits and foreign direct investment are two additional potential forms of private financing for adaptation. Export credits include guarantees, insurance, and other support that can help make developing country exports more competitive on the global market. Foreign direct investment is seen as having only limited potential for adaptation financing because it is highly concentrated in a few sectors and in a limited number of countries (Christiansen et al., 2012).

In both the public and private arenas, financing for adaptation is currently substantially less than financing for mitigation. According to an assessment of the total amount of climate finance available in 2009/2010 by Buchner et al. (2011), financing for mitigation outpaced financing for adaptation by a ratio of more than 20:1; whereas US$93 billion was provided for mitigation measures, only US$4.4 billion was directed to adaptation measures. Buchner et al. (2011) also noted that the vast majority (approximately 90%) of adaptation financing during that period came from public sources, primarily bilateral institutions. Private adaptation financing remains limited owing to market, institutional, and policy barriers that depress ROIs on these activities (World Bank Group, 2011). However, public-private partnerships that use public financing to leverage private investment are currently used to fund projects in several climate-sensitive sectors, such as infrastructure in the energy, transport, and water and sewage sectors (World Bank, 2011b; World Bank Group, 2011). These partnerships are not necessarily focused on climate adaptation, but can serve as models for future adaptation projects.

15.3. Strategies and Approaches

15.3.1. Diverse Strategies and Mixed-Portfolio Approaches

Strategies and approaches in adaptation planning and implementation vary according to context and level of government. National plans assume a coordinating role in adaptation actions for subnational and local levels of government, providing policy frameworks that guide decisions at the subnational level, spurring and coordinating the creation of legal frameworks, and directing action in key sectors for national development (Biesbroek et al., 2010; Bierbaum et al., 2013; see also Section 15.2.1). Subnational governments often have a complementary role to national governments by reflecting the governance structure in each country (West and Gawith, 2005; Lemmen et al., 2008; Karl et al., 2009; Pew Centre on Global Climate Change, 2009). States and provinces in a number of countries have begun to have an active role in CCA (Dinse et al., 2009; Staples, 2011; Barsugli et al., 2012; Bierbaum et al., 2013; Mukheibir et al., 2013).

In contrast, local level strategies are more diverse because climate change impacts occur locally and adaptation is context dependent. The scale of community engagement and the approaches used may provide key elements for the success of adaptation programs (Patt and Schröter, 2008; Ensor and Berger, 2009; Ford et al., 2011; Pelling, 2011; Picketts et al., 2012). Methodological guidelines for community adaptation plans and actions fostered by international organizations emphasize strategies focused on the use of local and traditional knowledge to increase adaptive capacity at the community level (IFRC et al., 2009; IISD, 2012; Crane, 2013). Moreover, community adaptation planning has been strengthened through the use of geographic information systems (GIS), modeling, climate change scenarios, ecosystem services, and other scientific research methods applied to foster the ability of the community to design adaptation (Shaw et al., 2009; Bardsley and Sweeney, 2010; IAPAD, 2010). Multilateral development agencies recognize the importance of inclusive approaches for adaptation planning and implementation, but they tend to focus on strengthening the role of local governments (USAID, 2007; OECD, 2009; Bizikova, 2010b; UNDP, 2010b; UN-HABITAT, 2011b; World Bank, 2011a; Abbas et al., 2012).

The diversity of approaches for local adaptation fosters opportunities for creating and strengthening adaptation planning and its implementation. But local governments and actors can face difficulties in making sense of such a diversity of approaches and identifying the most suitable and efficient approaches to follow, as mentioned in Section 15.2.1. Lessons learned from the DRM experiences illustrate that a lack of coordination occurs among the strategies taken to reduce the risk of disaster at the local level (ISDR et al., 2010; ISDR, 2011). Local CCA strategies can face similar problems. To be effective, local governments and actors critically identify, select, and combine the strengths of diverse approaches. The coordinating role of national and subnational governments can provide support in this direction. However, multilevel institutional coordination between different political and administrative levels in society can be an institutional barrier to planning and implementation in developed and developing countries (Few et al., 2007b; Urwin and Jordan, 2008; Corfee-Morlot et al., 2009; Keskitalo, 2009; Pahl-Wostl, 2009; Measham et al., 2011; Robinson and Berkes, 2011; Sietz et al., 2011; Rodima-Taylor et al., 2012; Nilsson et al., 2012; Glaas and Juhola, 2013). There appear to be few national guidelines to assist local governments in selecting relevant approaches (Storbjörk, 2007; Glaas et al., 2010; Mozumder et al., 2011; Adhikari and Taylor, 2012; Carmin et al., 2012; Hedensted Lund et al., 2012; Peach Brown et al., 2013). Similar barriers have been reported in DRM (ISDR et al., 2010; ISDR, 2011). A combination of top-down and bottom-up activities may strengthen local adaptation planning and implementation (Urwin and Jordan, 2008; Bulkeley et al., 2009; Preston et al., 2013). Connecting adaptation planning strategies and local development needs and plans (USAID, 2007; OECD, 2009; Bizikova et al., 2010b; UNDP, 2010a; UN-HABITAT, 2011b; World Bank, 2011a; Abbas et al., 2012) and the use of low-regret strategies can also support local adaptation strategies and their implementation (Hallegatte, 2009; UNDP, 2010a).

15.3.2. Adaptation and Disaster Risk Management

The UN Hyogo Convention (2005–2015) has fostered the creation of a significant number of disaster risk management (DRM) plans and actions at the national and local level in developed and developing countries (ISDR, 2011). The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) (IPCC, 2012) highlighted the complementary aspects and differences between DRM and CCA. Measures that provide benefits under current climate and a range of future climate change scenarios, called low-regrets measures, have been identified as starting points for addressing projected trends in exposure, vulnerability, and climate extremes in national and regional adaptation plans (see Section 8.3.2.2). These measures have the potential to offer benefits now and lay the foundation for addressing projected changes. Furthermore, the evaluation of DRM implementation helps to strengthen CCA because climate change impacts and DRM are key elements of adaptation and have a prominent role in these early stages of CCA (Few et al., 2007b; Hofstede, 2008; Mitchell et al., 2010; Garrelts and Lange, 2011; Harries and Penning-Rowsell, 2011; Rosenzweig et al., 2011; Rumbach and Kudva, 2011; Etkin et al., 2012; IPCC, 2012).

DRM includes managing hazards from extreme weather events and helps communities to deal with the uncertainty of climate change (Mitchell et al., 2010). On the other hand, disaster risk management strategies often fail to account for the differing spectrum of threats, and time and spatial scales needed to address the root causes of climate change vulnerability and open opportunities for CCA (Etkin et al., 2012). Proponents of merging DRM with CCA stress the mutual benefits of this approach. They also note that, currently, CCA and disaster risk reduction are within separate agencies, although they share similar objectives and challenges that can duplicate efforts if there is not an effort towards better coordination and integration (USAID, 2007; IFRC et al., 2009; Bizikova et al., 2010a; UNDP, 2010b; UN-HABITAT, 2011b; Abbas et al., 2012; EIRD, 2012; Turnbull and Turvill, 2012).

Current institutional structure and operation cultures are not congruent with the need for multidimensional approaches for DRM at the national and local level in a number of countries (ISDR et al., 2010; ISDR, 2011). This chapter identified similar institutional barriers in adaptation planning and implementation discussed in Section 15.5.1.2 (Few et al., 2007b; Urwin and Jordan, 2008; Corfee-Morlot et al., 2009; Keskitalo, 2009; Pahl-Wostl, 2009; Measham et al., 2011; Robinson and Berkes, 2011; Sietz et al., 2011; Nilsson et al., 2012; Rodima-Taylor et al., 2012; Glaas and Juhola, 2013). Addressing these institutional barriers in DRM and CCA jointly can help create more efficient and effective strategies and actions to adapt to short-, middle-, and long-term climate impacts. Planning has been highlighted as key tool for DRM and adaptation but it requires also transformations in its operational structure and practices to fulfill this role (Wilson, 2006; Blanco and Alberti, 2009; Roberts, 2010; Preston et al., 2011; Carmin et al., 2012; Mathew et al., 2012; Rodima-Taylor et al., 2012; Sanchez-Rodriguez, 2012).

DRM experiences reveal the importance of linking development and disaster risk prevention and reduction. Strengthening the integration of CCA with development has been also suggested (Lemos et al., 2007; Ewing et al., 2008; Hodson and Marvin, 2009; Hardee and Mutunga, 2010; Sietz et al., 2011). Connecting DRM and CCA to existing development pressures, agendas, policies, governance structures, and communitywelfare can help reduce the risk of unintended consequences of adaptation. DRM would also facilitate the support and acceptance of adaptation by decision makers and stakeholders at the subnational and national level (Dovers, 2009; Sovacool et al., 2012). Integrating DRM and CCA with development strategies, policies, plans, actions, and pressures can help address social vulnerability to climate change while providing opportunities for adaptation.

National and local efforts in disaster risk reduction recognize the importance of considering DRM a continuous learning process. Adaptation to climate change can also be viewed as a continuous learning process (not a single outcome), requiring regular monitoring and evaluation, as climatic and socioeconomic conditions change, and knowledge of the impacts increases (Adger and Barnett, 2009; Hinkel et al., 2009; Hulme et al., 2009; Preston et al., 2009; Arnell, 2010; Hofmann et al., 2011). Considering DRM and CCA learning processes assists in creating integrated approaches for national and local development strategies and plans. The process can also attend to intersecting social processes and help alleviate differing vulnerabilities that result from inequalities in socioeconomic status, income, and exposure to climate risks.

Lessons from DRM highlight the importance of participatory approaches and the use of local knowledge in the design and implementation of disaster risk prevention and reduction and CCA (Few et al., 2007b; van Aalst et al., 2008; ISDR et al., 2010; UNDP, 2010b; EIRD, 2012). By the same token, local knowledge-based adaptation is primarily focused on the use of traditional knowledge to increase adaptive capacity at the community level (see Table 15-1 for examples). Local knowledge often highlights vulnerabilities and impacts that may not be well known owing to the close interactions between climatic and non-climatic stressors associated with structural inequalities to vulnerability in societies (exposure, sensitivity, and adaptive capacity) (Majule et al., 2013). Combining top-down and bottom-up approaches and using low-regret strategies and actions in DRM and in adaptation planning and implementation increase climate resilience, improve livelihoods, reduce development pressures, and strengthen economic and social well-being (Moser and Satterthwaite, 2008; Hallegatte, 2009; Bizikova et al., 2010b; UNDP, 2010b). It can also help alleviate the concerns of limiting the effectiveness of policy interventions, as mentioned in Section 15.2.1.

15.3.3. Adaptation and Development

Discussions of the relationships between sustainable development and climate change have increased over the past decades (Cohen et al., 1998; Yohe et al., 2007; Bizikova et al., 2010a). As impacts of climate change hinder the achievement of development goals at all scales, O'Brien et al. (2012) emphasize that disaster risk management is increasingly considered as one of the frontlines of adaptation, and a promising arena for mainstreaming or integrating climate change adaptation into sustainable development planning. In many cases, the most attractive adaptation actions are also those that offer development benefits in the near term, as well as reductions of vulnerabilities in the longer term (Agrawala, 2005; Klein et al., 2007; McGray et al., 2007; Hallegatte, 2008; NRC, 2010). In developing countries, adaptation has been embedded in the development context in NAPAs and national adaptation strategies.

Attention to the social dimensions of adaptation, including rates of change in social conditions, in part of the literature coincides with the interest of international organization and scholars in the relationship between adaptation planning and implementation and development (UNDP, 2004; Lemos et al., 2007; Dovers, 2009; OECD, 2009; Stringer et al., 2009; Bizikova et al., 2010b; UN-HABITAT, 2011b). The literature supports the standing contention that adaptation takes place as a response not just to climate change but also to multiple stresses (Adger et al., 2005; Thomas and Twyman, 2005). Linking existing policy, agendas, knowledge, risks, and issues communities already face with adaptation planning can help reduce the unintended consequences of adaptation (Dovers, 2009). The importance of climate change adaptation is also influenced by how the issue is framed. For example, to the extent that it is viewed as a public safety issue or a development issue, it may have greater resonance within local government (Measham et al., 2010). Other authors consider integrating local knowledge and experience, including households, into multidimensional and multiscale approaches to guide the construction of adaptation responses to climate change, and integrate them with development strategies (Ewing et al., 2008; Moser and Satterthwaite, 2008; Blanco and Alberti, 2009; Hodson and Marvin, 2009).

Other literatures emphasize the role of planning as a switchboard for adaptation and development (Füssel, 2007; Hallegatte, 2009; Preston et al., 2011). This might require systemic changes to enable planning approaches capable of managing complexity and uncertainty, and multidimensional and multilevel coordination (Pahl-Wostl, 2009; Tompkins et al., 2010; Huntjens et al., 2011, 2012).

15.4. Tools Used for Decision Making, Planning, and Implementation

15.4.1. Decision Support Tools

A feature of adaptation planning is decision making under uncertainty. There is a large body of literature that examines how to integrate uncertain information into decision-making processes and use this information to evaluate the significance of uncertainties for decision outcomes. Treatment of uncertainty is dealt with in Section 2.3.1. Adaptation decision making is informed by various tools present in both top-down and bottom-up forms. Top-down tools often include downscaled simulated climate scenarios for regional level projections, accompanied by expert opinions. These are applied using multi-criteria optimization methods, evaluation of feasibility that may include cost effectiveness such as cost-benefit analyses, and assessment of potential impact severity (Carter et al., 1994; IPCC-TGICA, 2007; Adger et al., 2009a,b; see also Sections 5.5.3, 9.4.2). In the bottom-up approach, those affected or at risk examine their own impacts and vulnerabilities and incorporate adaptive options for the appropriate sector or community. Stakeholders may organize social and institutional activities in the light of actions and interactions among those engaged in the process. Advances in stakeholder participatory methods have significantly enhanced the development of this type of decision-making tool in recent years (Epstein and Axtell, 1996; Wolfram, 2002; Kaner et al., 2007; see also Section 2.4.4).

No single tool suits all circumstances of adaptation decision making, although information development tools such as Community-based Risk Screening Tool-Adaptation and Livelihoods (CRiSTAL) can manage diverse vulnerabilities and risks (IISD, 2012). By outlining the problems and the available inputs to the adaptation decision process, this tool may provide a suitable option (Gimblett, 2002). IPCC (2012) notes there are distinct differences in problem orientation and solution space depending on whether an adaptation plan commences with climate modeling outputs versus that of a risk- and vulnerability-based framework.

15.4.2. Tools for Planning

Uncertainties in climate change, coupled with the complexities of social-ecological systems, require a dynamic approach to adaptation planning and implementation. Knowledge about climate change risks from various stakeholders and organizations is an essential resource for adaptation planning. Multidisciplinary efforts, some of which are discussed below, have engaged in development, assessment, and communication of climate information and risks across different time scales.

15.4.2.1. Monitoring, Modeling, and Spatially Integrated Tools

Integration of monitoring and/or modeling systems with the techniques of GIS can strengthen adaptation planning and implementation. The complex, multiscale, interdisciplinary nature of climate change impacts on socio-ecological systems has made the computer-based modeling approach a tool for understanding the evolving processes and future conditions (Alter, 2004; Pyke et al., 2007). These include remote-sensing and global positioning systems and discussion support or a dynamic dialog between researchers and practitioners. As a result, much more powerful, process-visual, and spatially implicit decision-support systems have been developed. One example is the development of the Invasive Species Forecasting System (ISFS) (Stohlgren et al., 2005) that combines USGS science and NASA Earth observations with software engineering to provide regional-scale patterns of invasive species and vulnerable habitats. Similarly, in the Yellow River, the second largest drainage basin of China, low-flow seasons caused the lower channel to dry up and forced governments to develop a basin-scale decision-support system (Li and Li, 2009). The European Spatial Planning Adapting to Climate Events Project (ESPACE) asserts that urban planning contributes to adaptive efforts by utilizing tools for adaptation through both conventional and green infrastructure and design (porous surfacing, green roofs, etc.) (ESPACE, 2008).

15.4.2.2. Communication Tools

There are a wide range of communication tools that can play an important role in adaptation implementation. These tools include brochures, bulletins, posters, magazines, policy briefs, videos, TV and radio broadcasts, Internet, and many more that are being employed to carry out participatory dialogs. These provide avenues for communication among information developers (e.g., scientists, trainers, project implementers, government agencies, etc.) and community members, groups at risk, etc., who also influence the nature of information disseminated. At the local level, interactive strategies include theater, role-playing, music, learning-by-doing, and hands-on exercises. There are also group discussions of community members to debate climate risks and possible solutions to cope with impacts that positively affect behavior and practices. Reports, concept notes, brochures, magazines, presentations, and workshops provide more effective tools to communicate with policy makers at local and national levels. At the country/regional level, broad dissemination channels such as TV, radio and internet broadcast, blogs, and high-level summits have been effective in creating widespread awareness, as demonstrated in the Advancing Capacity for Climate Change Adaptation (ACCCA) project (http://www.acccaproject.org/accca/), UK Climate Impacts Program (UKCIP; Pringle, 2011), and the SREX report (IPCC, 2012).

To assist the syntheses, a variety of rule- or matrix-based methods have been applied for screening adaptation options such as relative cost effectiveness of alternative adaptation measures (Benioff and Warren, 1996), and for adaptive opportunities for coastal zone management (Uljee et al., 1999). Greater emphasis on user interaction, sensitivity analysis, and capabilities currently provides more effective visualization and customized reports (Sarewitz et al., 2000; Sarewitz, 2004). Multi-criterion and multi-actor participatory approaches allow users to consider alternative adaptation strategies and evaluate trade-offs, typically in the development of tools for environmental assessment and management (Julius and Scheraga, 2000).

15.4.2.3. Early Warning and Information Systems

Monitoring and early warning systems (EWS) have long played important roles in helping in adjustment and adaptation especially on the local

Box 15-1 | Examples of Tools and Measures

Conventional and Green Infrastructure

- Large investment has been made on engineered structure to protect coastal areas against climate-related events. In New York City, infrastructure adaptation strategies to climate change include both hard and soft measures. Hard structures in the New York City region include seawalls, groins, jetties, breakwaters, bulkheads, and piers, but these have not yet been strengthened and elevated over time in response to projected rates of sea level rise (Gornitz, 2001). Storm-surge barriers have been recommended to protect against high water (Aerts et al., 2009; Zimmerman and Faris, 2010). Such barriers are also used in the Thames in London (UK Environment Agency, 2012; see Box 5-1) and Rotterdam (Aerts et al., 2009). Soft measures involve wetland and dune restoration, beach nourishment, enhancement, and expanding the Staten Island Bluebelt—a stormwater management system to other areas (NYCDEP, 2008).
- In the Netherlands, during the second half of the 20th century, large structures had been built to protect the coastal area (Kabat et al., 2009). To keep the country flood-proof over the 21st century, an estimated total cost of implementing a new ambitious plan is €2.5 to 3.1 billion a year to 2050, representing 0.5% of the current Dutch annual gross domestic product (GDP) (Stive et al., 2011). The new plan is a paradigm shift that addresses coastal protection "working with nature" and providing "room for river" instead of only "fighting" the forces of nature with engineered structures.
- Development of engineered structures can lead to more greenhouse gas emissions and potential negative impacts on ecosystems (see Section 5.5.6). On the contrary, green infrastructure (porous surfacing, green roofs, etc.) have been used in parts of Europe (ESPACE, 2008), Portland, Philadelphia, New York (Foster et al., 2011), London (GLA, 2011), and Quy Nhon in Vietnam (Brown et al., 2012) (see Section 8.3.3.7).

Use of Information and Communication Technologies

- Information and communication technologies (ICTs) can help strengthen the physical preparedness of livelihood systems for climate change-related events. These can contribute to design of defenses and determination of their optimal location, and make the livelihood system more robust. GIS technology was applied to foster the ability of the community to deal with climate change hazards and trends in the Philippines (IAPAD, 2010) and form modeling processes of climate change adaptation that supported regional stakeholders to develop better protection of key spaces in the landscape (Bardsley and Sweeney, 2010). Visualization of sea level rise and climate change damage in Delta in British Columbia, Canada, increased awareness of long-term risks and response challenges to local community, government, and the public (Shaw et al., 2009).
- By sharing observations and reflections through ICT tools, users foster new ways of assimilating or translating information, which can be shared through wider networks, and then influence action, enabling new experiments/practices to take place. This generation of new and broader learning cycles will in turn strengthen systematic resilience (Ospina and Heeks, 2010). Karanasios (2011) outlines the range of new and emergent ICTs (e.g., wireless broadband, sensor networks, GIS and Web-based tools) being applied to climate change issues, and investigates their use in developing countries.

Other Tools

- Other tools are being used such as insurance (see Section 8.4.2; Table 10-8), linking CCA to ICZM (Section 5.5.3) or DRR (Section 8.3.2.2), reduction of emissions from deforestation and forest degradation (Section 13.3.1.2), using climate change scenarios (Box 14-1), ecosystem-based adaptation (Box CC-EA, Box 8-2, Section 22.4.5.6, Figure 22-6), and land use (Box 25-10).

scale. The disaster research community has shown that successful warnings of impending events are those that are complemented by information on the risks actually posed by the hazards and by potential strategies and pathways to mitigate damage within a particular context (Drabek, 1999; UNISDR, 2006). The use of climate data analyses and projections in early warning and information systems is an important and established mechanism to inform disaster risk mitigation (Pulwarty and Verdin, 2013) or climate-related health risks (see Section 11.7.3). It helps to ensure the link between generation and application of climate knowledge for management of climate-related risks and CCA. In this regard, interest in climate services is growing in many countries (see Section 2.4.1).

EWS includes a diversity of approaches. These range from technological advances in systems, satellite information, and climate modeling (UNISDR, 2006; Smith et al., 2009; Bierbaum et al., 2013) to local level early warning based on traditional knowledge needed to develop and inform strategic response options in adaptation planning and implementation. Local knowledge can be complemented with scientific climatic data, research, and planning tools (GIS, modeling, etc.) to strengthen community-based monitoring and vulnerability assessment in disaster risk management and adaptation to climate change (Green and Raygorodetsky, 2010; Kalanda-Joshua et al., 2011; Newsham and Thomas, 2011; Nakashima et al., 2012).

Current science and technology do not resolve the uncertainties in modeling the response of ecosystems to climate change and management interventions at levels needed for probabilistic early warning. Yet the need for precise climate information is often overstated (Smith et al., 2009). The long-standing experience with climate extremes and variability offers many usable lessons in spite of these uncertainties. The impacts of climate change will be most strongly felt by populations vulnerable to changes in the distribution and magnitude of extreme weather and climate events, as these affect crops, disease outbreaks, and soil and water quality. The diverse types of EWS in developed and developing countries are valuable tools that could help societies develop strategies to cope and adapt to climate-related risks.

15.4.3. Technology Development, Transfer, and Diffusion

Development and diffusion of technologies and management practices will continue to be critical to many adaptation efforts. While a wide range of adaptations are possible with current technologies and management practices, technologies expand the range of adaptation possibilities by expanding opportunities or reducing costs (Smith et al., 2009). Technologies related to information collection and diffusion are particularly important for adaptation planning, including technologies for data collection and information dissemination during extreme events and emergencies. Despite remaining uncertainties, technologies to project climate changes, and identify potential impacts and vulnerabilities, are frequently seen as precursors to successful adaptation planning. Developing countries require enhanced access to improved climate models, but also adaptation planning tools that focus on robustness in the face of uncertainty (Dessai et al., 2009).

Technology choices can both reduce and exacerbate risk, and their use in adaptation planning and implementation requires considering their potential effects (Jonkman et al., 2010). For example, technologies can strengthen physical infrastructure, such as bridges and buildings, so that they can withstand more extreme hazards. However, relatively centralized high-technology systems increase efficiency under normal conditions but risk cascading malfunctions in the event of emergencies. In some circumstances, technologies to reduce short-term risk and vulnerability contribute to increased future vulnerability to larger extreme events (Etkin, 1999; Moser, 2010). This was seen in the impacts of Hurricane Katrina on New Orleans, where a flood defense system enabling construction in a floodplain was subject to catastrophic failure in the face of a particularly large extreme event (Freudenburg et al., 2008; Link, 2010).

International efforts for technology transfer have been concentrated in the UNFCCC framework's five themes: technology needs and needs assessments, technology information, enabling environments, capacity building, and mechanisms for technology transfer. A key project is developing a technology transfer clearinghouse called TT:CLEAR, and establishing a Technology Center and Network (UNFCCC, 2012). However, successful technology transfer requires not only exchange of technological solutions, but also strengthening policy and regulatory environments, and capacities to absorb, employ, and improve appropriate technologies. In both developed and developing countries, multilateral institutions can support collaboration that engages private interests in regulatory planning and possibly activities, particularly if ongoing funding is expected (Tessa and Kurukulasuriya, 2010).

15.4.4. Insurance and Social Protection

Insurance is widely seen as a cost-effective tool for adaptation planning and implementation for increasing financial resilience, especially when compared to *ex post* disaster aid (Warner et al., 2009; Linnerooth-Bayer et al., 2011). It is in this context that insurance has received the attention of those planning and managing climate adaptation: IPCC's SREX report (IPCC, 2012) recognizes that risk sharing and transfer mechanisms at local, national, regional, and global scales can increase resilience to climate extremes, while for slow-onset impacts it is usually considered unsuitable (Collier et al., 2009). The main question is if and how insurance products, particularly natural disaster and agricultural cover, can be designed so that they trigger adaptive behavior. The insurance price signal is widely considered as the first step in taking risk reduction measures (Fankhauser et al., 1999), but it does not imply that action will be taken. In fact those at risk, such as local farmers, may not have the capacity to act because they lack tools, methods, or financial means. The role of insurance is also discussed in Section 10.7 in this report.

Many scholars agree on the theoretical potential for insurance to facilitate climate risk reduction through a wide scale of activities, ranging from awareness raising and sharing of modeling and risk mapping data and tools, to providing economic incentives for risk reduction and mandating adaptation as a condition for granting insurance (Crichton, 2008; Suarez and Linnerooth-Bayer, 2011; Surminski and Oramas-Dorta, 2011; Paudel, 2012). Evidence of how this is successfully achieved is limited to private insurance and reinsurance companies, scientists, and governments aiming at adaptation, most notably through sector initiatives such as ClimateWise and UNEPFI's Insurance Working Group (Mills, 2004). Existing insurance schemes for flooding in the USA (Michel-Kerjan and Kunreuther, 2011) and the UK (Ball et al., 2013) show the challenges of fostering risk reduction through insurance. Those two schemes are on opposite ends of a broad scale—the U.S. National Flood Insurance Program being a public sector scheme, while the UK's flood insurance is provided by a private insurance market. Both systems struggle with the implementation of risk-based pricing as the guiding principle of insurance. Picard (2008) highlights the trade-off between effectiveness of risk based pricing and equity—as those most vulnerable struggle to pay for risk-based premiums. Public-private partnerships may be able to assist through premium subsidies, or broader collaboration on risk management, as seen in the case of the UK's flood insurance.

The use of insurance to manage extreme weather events varies across the world, with penetration of insurance coverage determined mainly by income levels (Ranger and Surminski, 2012), with insurance in most low- and middle-income countries still in its infancy (Churchill, 2007; Warner et al., 2009). Demand-side limitations include access to and affordability of coverage, desirability of products, and financial literacy (Linnerooth-Bayer et al., 2011).

Over the last decade, risk transfer schemes have been developed in low-income countries, often run as pilot projects between the private sector and public authorities. Analysis of the existing disaster risk transfer activities in low- and middle-income countries indicates that the potential for utilizing risk transfer for risk reduction is far from exhausted, with only very few schemes showing an operational link between risk transfer and risk reduction (Surminski and Orama-Dorta, 2011; IPCC, 2012, p. 355). Some innovative efforts are currently being tested to address these challenges—such as the El Niño-Southern Oscillation (ENSO) insurance scheme in Peru, an index-based forecast insurance that pays out on the basis of a seasonal forecast, giving policyholders the opportunity to use the pay-out for preventive measures, such as the purchase of drainage cleaning machinery or to improve transport infrastructure or adjust cash flows in anticipation of possible income reduction (GIZ, 2012). A regional insurance system is also an innovative tool for sharing disaster risks among participating countries. For example, the Caribbean Catastrophic Risk Insurance Facility (CCRIF) was established as a risk pooling facility, attended by 16 countries, to limit the financial impact of catastrophic hurricanes and earthquakes to Caribbean governments by quickly providing short-term liquidity. Another approach is the agricultural insurance scheme in Sudan, where farmers are required to adopt more resilient farming practices to gain access to the risk transfer scheme and the Horn of Africa Risk Transfer for Adaptation (HARITA) scheme in Ethiopia (Oxfam, 2009).

There are various adaptation options that target the specific vulnerability of disadvantaged groups as social options of CCA. Social protection programs include public and private initiatives that transfer income or assets to poor people, protect against livelihood risks, and raise the social status and rights of the marginalized (see Glossary). The roles of social protection in CCA are discussed in Section 14.3.2 and Box 13-2.

15.5. Governance for Adaptation Planning and Implementation

15.5.1. Institutional Dimensions for Planning and Implementing Adaptation

15.5.1.1. Importance of Institutional Dimensions

Since the AR4 findings on substantial barriers to mainstreaming adaptation and suggested research challenges in further understanding adaptation processes of mainstreaming adaptation (Adger et al., 2007), the academic literature identifying drivers and barriers to climate adaptation planning and implementation has increased. A recent review has shown that more than 200 context-dependent barriers have been identified in 81 peer-review papers, mostly but not exclusively based on small-*N* inductive case studies (Biesbroek et al., 2013). The message from the literature is clear: adaptive capacity signals potential but does not guarantee adaptive action (O'Brien et al., 2006; Adger and Barnett, 2009; Burch, 2010; Tompkins et al., 2010). While there is growing recognition that adaptation planning is essential (Ayers and Huq, 2009; Wilbanks and Kates, 2010; Ford et al., 2011), research reporting on planning and implementation has increased appreciation of the magnitude of the institutional dimension for limiting or enabling the mainstreaming of climate adaptation (Moser and Ekstrom, 2010; Berkhout, 2012; Biesbroek et al., 2013). Several studies, in different settings, for example, river basin management in Brazil (Engle and Lemos, 2010), municipalities in Canada (Burch, 2010) and Australia (Measham et al., 2011), villages in Western Nepal (Jones and Boyd, 2011), and pastoralist groups in Kenya (Eriksen and Lind, 2009; Robinson and Berkes, 2011; Adhikari and Taylor, 2012), illustrate such difficulties. Adaptation studies, targeting specifically how institutional dimensions limit or enable the mainstreaming of climate change considerations in policy making, planning, and decision making at different levels and in different sectors, have grown in number (Crabbé and Robin, 2006; Koch et al., 2007; Roberts, 2008; Bulkeley et al., 2009; Engle and Lemos, 2010; Glaas et al., 2010; van den Brink et al., 2011; Storbjörk and Hedrén, 2011; Huntjens et al., 2012; Termeer et al., 2012; Glaas and Juhola, 2013).

Institutions are composed of tangible formal procedures, laws and regulations and tacit informal values, norms, traditions, codes, and conducts that shape expectations and guide actions among actors and organizations, serving as manifestations of institutions (Ostrom, 1990; Dovers and Hezri, 2010). Adaptation planning and implementation follows formal institutions associated with regulations, policies, and standards created and enforced by government actors but also requires the participation of informal institutions through interactions among stakeholders according to cultural, social, and political conditions in societies (Moser and Satterthwaite, 2008; Carmin et al., 2012). Chapter 14 describes the importance of these institutional frameworks for adaptive capacity. Chapter 16 presents a framework for adaptation, opportunities, and limits, where governance and institutional arrangements are included. This section assesses the literature on how institutional dimensions limit or enable adaptation planning and implementation and what lessons can be learned from these experiences.

15.5.1.2. Institutional Barriers

While the literature clearly states that institutional dimensions may both enable and limit adaptation planning and implementation, the literature referred to in Section 15.5.1.1 has so far mostly reported on how current institutional arrangements restrict the mainstreaming of climate adaptation. Biesbroek et al. (2013) have stated that although studies in developed countries are more common and comparative approaches of institutional dimensions, exploring differences and similarities in different countries, are rare, institutional dimensions are highlighted for both developing and developed countries. Low-income developing countries report on weak institutional environments and middle- and high-income countries emphasize institutional barriers that prevent the mobilization of adaptive capacity. Barriers in general are seen as dynamic and context dependent across sectoral, spatial, and temporal scales, meaning that how a particular institutional barrier operates to either strengthen or limit adaptation planning and implementation can vary both between and within countries, depending on case study locations. Also, the importance and severity of each barrier to the proposed change supposedly changes over time and interacts with other constraints (Burch, 2010; Moser and Ekstrom, 2010; Biesbroek et al., 2013). Barriers are also shown to differ in different stages of planning and implementation, for example, initial problem framing and agenda setting, planning and strategy-making, implementation, monitoring, and evaluating, which studies have increasingly made clear (Moser and Ekstrom, 2010; Dannevig et al., 2012; Mees et al., 2012). The following paragraphs illustrate five of the most commonly emphasized barriers or enablers of institutional change.

First, the importance of multilevel institutional coordination between different political and administrative levels in society is increasingly cited in both developing and developed countries as challenging (Few et al., 2007a; Urwin and Jordan, 2008; Corfee-Morlot et al., 2009; Keskitalo, 2009; Pahl-Wostl, 2009; Measham et al., 2011; Robinson and Berkes, 2011; Sietz et al., 2011; Nilsson et al., 2012; Rodima-Taylor et al., 2012; Glaas and Juhola, 2013). Several studies report on unclear roles and responsibilities between levels and actors inhibiting climate adaptation. They show that there are few national requirements or guidelines to help local governments approach climate adaptation, stressing the importance of developing regulations, policies, and codes to support the institutionalization of local climate actions (Næss et al., 2005; Crabbé and Robin, 2006; Storbjörk, 2007; Glaas et al., 2010; Mozumder et al., 2011; Adhikari and Taylor, 2012; Carmin et al., 2012; Hedensted Lund et al., 2012; Peach Brown et al., 2013). Vammen Larsen et al. (2012) stress that climate change does not possess clear institutional characteristics as a municipal professional area. Rather, it is viewed as a void with no clear rules and norms according to which politics are to be conducted and policy measures agreed on. This has meant that climate adaptation remains ad hoc and based on processes of "muddling through" in a sense that increases risks of failure (Preston et al., 2011).

Further, the literature shows that the lack of clear national agendas and incentives may burden local governments differently, based on their different capacities (Anguelovski and Carmin, 2011; Juhola and Westerhoff, 2011; Dannevig et al., 2012). Authors have also cautioned against a too heavy emphasis on national guidance, suggesting that centralized approaches may in some cases constrain local initiatives and create unfortunate dependencies. Instead a combination of top-down and bottom-up activities is proposed where national actors set a proactive agenda for climate adaptation and support implementation that occurs at subnational levels (Urwin and Jordan, 2008; Bulkeley et al., 2009; Preston et al., 2013). Connected to this question of guidance and support is also a large strand of research showing that simply producing more and better knowledge is not sufficient. This illustrates the role of knowledge-brokers, policy entrepreneurs, and bridging organizations to communicate and mediate the co-production of knowledge between science and practice and make climate knowledge consistent and credible at the appropriate decision-making scale (Tribbia and Moser, 2008; Amundsen et al., 2010; Tompkins et al., 2010; Mozumder et al., 2011).

Second, the literature show that key actors, advocates, and champions are decisive for initiating, mainstreaming, and sustaining momentum for climate adaptation planning and implementation in different national settings (Bulkeley et al., 2009; Burch, 2010; Moser and Ekstrom, 2010; Tompkins et al., 2010; Garrelts and Lange, 2011; Runhaar et al., 2012; Romero-Lankao, 2012). Key actors can be particularly important in the absence of strong national level policies and strategies (Anguelovski and Carmin, 2011; Dannevig et al., 2012). Champions further involve actors in different roles, from junior staff to senior executives and elected representatives (Measham et al., 2011). The literature on leadership has distinguished between different types of leadership, where visionary leadership means showing direction and motivating others; entrepreneurial leadership means ability to get things done; and, finally, collaborative leadership means bridging gaps, spanning boundaries, and building coalitions (Gupta et al., 2010; van den Brink et al., 2011). Although there is wide agreement that leaders are key for driving change, a dependency on personal commitments and dedication of key individuals may render adaptation planning and implementation fragile if it takes place at the price of organizational learning (Næss et al., 2005; Crabbé and Robin, 2006; Storbjörk, 2010).

Third, the horizontal interplay between actors and policies operating at similar administrative levels is seen as key in institutionalizing climate adaptation. Several international studies have shown that local governments and administrations consist of different professional silos with their own internal norms, values, and priorities and that the institutional rigidity of existing administrative and political sectors creates unfortunate compartmentalization where climate adaptation is seen as the isolated task of a singular sector that may hinder mainstreaming and horizontal coordination across sectors and departments (Mickwitz et al., 2009; Burch, 2010; Roberts, 2010; Storbjörk, 2010; Runhaar et al., 2012; Vammen Larsen et al., 2012; van den Berg and Coenen, 2012; Wilby and Keenan, 2012). Preston et al. (2011) have determined that adaptation plans from Australia, the UK, and the USA largely frame adaptation in a narrow sense overlooking the capacity and institutional challenges involved in the process of mainstreaming in other sectors. Institutional rigidity also takes the form of path dependency where past policies, decisions, habits, and traditions constrain the extent to which systems can learn or adapt to climate change (Garrelts and Lange, 2011; Berkhout, 2012; Runhaar et al., 2012; Preston et al., 2013). Some authors have identified such cultures of reactive management or structural engineered approaches to climate adaptation negatively influencing institutional change (Næss et al., 2005; Harries and Penning-Rowsell, 2011; Measham et al., 2011). Several writers have emphasized the need to facilitate improved cross-sectoral interaction, exchange, and organizational learning to drive institutional change (Berkhout et al., 2006; Crabbé and Robin, 2006; Pelling et al., 2008; Hinkel et al., 2009; Burch, 2010). How cross-sectoral coordination is achieved in practice remains one of the major challenges in transitioning from planning to implementation.

Fourth, the need to acknowledge political dimensions in planning and implementation is highlighted in several studies, both in developing and developed countries. Studies indicate that politicians have not recognized climate adaptation as being politically urgent enough to elevate on the policy agenda. Subsequently they identify a tendency to prioritize other political concerns, often more short-term tangible issues (O'Brien et al., 2006; Storbjörk, 2007; Glaas et al., 2010; Corfee-Morlot et al., 2011; Measham et al., 2011; Runhaar et al., 2012; Preston et al., 2013). This has implications for the availability of resources and financial means in the form of staff and time (Tribbia and Moser, 2008). Other studies document competing values, conflicting objectives, tensions, and trade-offs between different policy agendas and priorities in planning and implementing climate adaptation (Næss et al., 2005; Berkhout et al., 2006; Adger et al., 2009a; O'Brien and Wolf, 2010; Measham et al., 2011; Storbjörk and Hedrén, 2011). In a developing country context, a study in the drylands of Kenya calls for increased consideration of political dimensions of local adaptation by showing how power relations at multiple geographic scales and interaction of informal institutions, for example, clans and spiritual leaders and government institutions, shape the local negotiation of conflicting interests (Eriksen and Lind, 2009).

Fifth, improved coordination between formal governmental and administrative agencies and private stakeholders is highlighted in the literature. Private sector involvement is often seen as a way to increase the efficiency of climate adaptation (Engle and Lemos, 2010; Mees et al., 2012; Tompkins and Eakin, 2012). As part of highlighting private sector involvement, studies from developing and developed countries emphasize the need for stakeholder participation, representation, accountability, and equality to influence the sharing and shaping of knowledge in adaptation decision making and achieve change on the ground (Gupta et al., 2010; Harries and Penning-Rowsell, 2011; Robinson and Berkes, 2011; Adhikari and Taylor, 2012; Huntjens et al., 2012; McNeeley, 2012; Tompkins and Eakin, 2012). Participatory approaches potentially allow maintaining regard for the highly localized and contextual nature of climate adaptation, balance standardization and context in adaptation planning and implementation, and bolster support for and facilitate implementation (Preston et al., 2011; Mees et al., 2012). Elaborate forms of participatory designs for facilitating a co-production of knowledge, interactive learning, and stakeholder exchange, mediated by boundary organizations and knowledge brokers, are being undertaken but more are needed (Pahl-Wostl, 2009; Pulwarty et al., 2009; Tompkins et al., 2010; Jonsson et al., 2012). At the same time authors clarify that stakeholders can hold private, sectarian interest and represent local elites, meaning that which voices actually get represented is an important issue (Romero-Lankao, 2012). Studies in western Nepal have documented obstacles to political inclusion due to social status and caste-based political discrimination where societal elites suppress marginal voices (Jones and Boyd, 2011). Other studies have documented how existing centralized top-down institutions have been complemented and sometimes challenged by public-private partnerships at critical stages in implementation (Juhola and Westerhoff, 2011; Rodima-Taylor et al., 2012).

15.5.1.3. Facilitating More Effective Climate Adaptation Planning and Implementation

Although Section 15.2 shows that international studies clearly report a large number of ongoing responses to support climate adaptation, which are most commonly incremental responses within existing institutional arrangements (with some rare examples of institutional transformations), there is a large body of evidence of the mainstreaming of climate adaptation resulting in limited implementation. Subsequently most studies on climate adaptation planning and implementation have focused on identifying barriers and challenges. Biesbroek et al. (2013) have suggested moving forward in our current context-specific and fragmented understanding of barriers, including institutional dimensions, and embrace comparative approaches, synthesizing knowledge and analyzing barriers more systematically. Recent discussions suggest focusing more attention on how to transform barriers to enablers of action and institutional change (Burch et al., 2010; Moser and Ekstrom, 2010; Park et al., 2012; Biesbroek et al., 2013). Dovers and Hezri (2010) have claimed that there is a predominant focus in adaptation research on what should happen rather than how that might be achieved, the latter targeting strengths and weaknesses with different forms of institutional structures, procedures, and ways of organizing climate adaptation that supports change. Others have suggested that monitoring and evaluating the effectiveness of strategies adopted and interventions undertaken needs further attention (Mullan et al., 2013). Further, it is suggested that propositions for change tend to be driven by theory rather than empirically substantiated and tested and that the adaptation literature would benefit by embracing lessons and experiences of mechanisms for enabling institutional change gained in other policy sectors and past policy interventions (Dovers and Hezri, 2010; Biesbroek et al., 2013).

15.5.2. Increasing Capabilities

Governance of adaptation creates the space and conditions for achieving specific goals or collective outputs by aligning principles and norms for regulations, decision-making procedures, and organizations in providing an overarching system to address a challenge comprehensively (Biermann et al., 2009; Young, 2010; DeWulf et al., 2011). However, the embryonic stage of adaptation planning and implementation faces challenges to develop governance approaches (Glaas et al., 2010; Gupta et al., 2010; Tompkins et al., 2010; Carmin et al., 2012; Huntjens et al., 2012; Rodima-Taylor et al., 2012; Mukheibir et al., 2013). The previous section on the institutional dimensions of adaptation in this chapter stressed the obstacles in current structures of national, subnational, and local governments to address complex and multidimensional problems (Wilson, 2006; Koch et al., 2007; Roberts, 2008; Bulkeley et al., 2009; Inderberg and Eikeland, 2009; Engle and Lemos, 2010; Glaas et al., 2010; Sietz et al., 2011; Storbjörk and Hedrén, 2011; van den Brink et al., 2011; Huntjens et al., 2012; Rodima-Taylor et al., 2012; Termeer et al., 2012; Vammen Larsen et al., 2012; Glaas and Juhola, 2013). Similar fragmented approaches for adaptation planning and implementation also hinder a dynamic and diverse participation of other stakeholders in these processes (Folke et al., 2005; Raschky, 2008; Urwin and Jordan, 2008; Coles and Scott, 2009; Dessai et al., 2009; Handmer, 2009; Scheffer, 2009; Nath and Behera, 2010; Reid et al., 2010; Sissoko et al., 2011). In addition, there have been very few documented changes in forecasts, plans, design criteria, investment decisions, budgets, or staffing patterns in response to climate risks (Repetto, 2008; Tompkins et al., 2010; Berrang-Ford et al., 2011).

Expanding and improving capabilities of stakeholders strengthen operational approaches for adaptation to climate change at different levels. The literature recognizes four areas where improved capabilities can facilitate this creation of governance approaches for adaptation planning and implementation: creating learning processes incorporating various knowledge systems and experiences to facilitate developing a common understanding and policies critical for cross-institutional coordination and multi-stakeholder actions (Engle and Lemos, 2010; Huntjens et al., 2012); enhancing monitoring and evaluation of adaptation planning and implementation currently limiting opportunities for learning and improvement of current and future adaptation initiatives (Manuel-Navarrete et al., 2009; Preston et al., 2011; Nilsson et al., 2012); improving cross-level coordination within government structures at the national, subnational, and local levels (Urwin and Jordan, 2008; Bulkeley et al., 2009; Amundsen et al., 2010; Robinson and Berkes, 2011; Preston et al., 2013); and enhancing the participation of stakeholders from the assessment of vulnerability to the design and implementation of operational approaches of adaptation (Moser and Satterthwaite, 2008; Anguelovski and Carmin, 2011; Carmin et al., 2012; Dannevig et al., 2012).

These interacting aspects strengthen incorporating climate change risks to systems and sectors, and the corresponding response planning and implementation actions occurring at different spatial and temporal scales. They help improve mechanisms to foster and strengthen coordination in the scale of governance together with a clear division of tasks and responsibilities of actors, especially under conflicting time scales of interventions (Koch et al., 2007; Amundsen et al., 2010; Biesbroek et al., 2010, 2011). They can also support addressing jurisdictional scales and mandates across sectors, and local, national, and subnational policies, constricting the potential benefits of close dependencies between institutions, institutional systems, and organizational units in planning and implementation of adaptation (Dovers and Hezri, 2010).

Creating capabilities through coordination is reported to expand the adaptive capacity of local actors and enhance opportunities for policy formulations of larger governance networks and learning opportunities for policy formulations (Keskitalo and Kulyasova, 2009; Owen, 2010). Capturing various perspectives of multiple stakeholders and actors holding different views, power, and influence is pivotal in mutually achieving short-term and long-term adaptation needs to climate change (O'Brien et al., 2008; Shaw et al., 2009; Bardsley and Sweeney, 2010; IAPAD, 2010; Corfee-Morlot et al., 2011). Capabilities to enhance and complement the value of local knowledge through scientific knowledge can become a useful source of community-based adaptation planning and implementation (McLeman et al., 2008; Green and Raygorodetsky, 2010; Berrang-Ford et al., 2011; Birkmann, 2011; Ford et al., 2011; Newsham and Thomas, 2011; Nakashima et al., 2012).

Increasing capabilities for adaptation planning and implementation can also benefit from approaches with greater emphasis on nature-based protection strategies or buffers. Related climate change adaptation efforts also improve ecosystem resilience by implementing sustainable forestry management, expanding floodplain setbacks, implementing coastal afforestation and coral reef propagation, restoring degraded lands, maintaining healthy vegetation on slopes, incentivizing development away from coastal areas and bluffs, and removing barriers to the migration of plants and animals, all of which are necessary for the resilience of communities facing climate change impacts (Tobey et al., 2010; Sovacool et al., 2012).

15.6. Research Needs for Maximizing Opportunities

The following interrelated research needs extracted from the chapter can create and maximize opportunities for adaptation planning and implementation.

The emphasis on impacts and defensive infrastructure has been documented in a number of early adaptation plans (Few et al., 2007a; Hofstede, 2008; Mitchell et al., 2010; Garrelts and Lange, 2011; Harries and Penning-Rowsell, 2011; Rosenzweig et al., 2011; Rumbach and Kudva, 2011; Etkin et al., 2012; IPCC, 2012). Research on the design and implementation of these plans and the lessons that can be extracted from them can help address concerns in the literature that an impact approach can overshadow the analysis of underlying stressors of hazards, the drivers of vulnerability, and opportunities for connecting development pressures and climate change (Lemos et al., 2007; Sabates-Wheeler et al., 2008; Boyd and Juhola, 2009; Hulme et al., 2009; Orlove, 2009; Hardee and Mutunga, 2010; Ribot, 2010; Rumbach and Kudva, 2011; Sietz et al., 2011). These lessons can help balance the design of adaptation planning including projects for defensive infrastructures needed through flexibility and safety margins and at the same time incorporating other actions seeking to reduce social vulnerability and enhancing adaptation. Relevant in these efforts is building a better understanding of how early adaptation plans can transcend from defensive but fragmented approaches to multidimensional policy process recognizing adaptation planning and its implementation as learning processes (Hulme et al., 2009; Biesbroek et al., 2011).

Research on operational strategies and approaches for adaptation can help maximize available resources for adaptation to climate change. Current contributions in the literature help build a better understanding on diverse dimensions of this complex process, but these contributions have provided little attention to the discussion and suggestion of guidelines to build operational approaches. Some authors stress that few studies show how adaptation to climate change is actually being delivered (Arnell, 2010; Tompkins et al., 2010; National Research Council, 2011). Key elements in these research efforts are: expanding knowledge of the connections between adaptation and development in different contexts and at different governance levels (Boyd and Juhola, 2009; Dovers, 2009; Hulme et al., 2009); the role of multiple stresses (not just climate) in adaptation planning and its implementation (IPCC, 2007; Tompkins et al., 2010); and the role of low-regret strategies strengthening operational approaches for adaptation (Hallegatte, 2009; UNDP, 2010a).

Section 15.5.1 highlights how limitations of current institutional arrangements restrict the mainstreaming of climate adaptation (Roberts, 2008; Burch, 2010; Dovers and Hezri, 2010; Engle and Lemos, 2010; Glaas et al., 2010; Moser and Ekstrom, 2010; Jones and Boyd, 2011; Robinson and Berkes, 2011; Storbjörk and Hedrén, 2011; Dannevig et al., 2012; Huntjens et al., 2012; McNeeley, 2012; Vammen Larsen et al., 2012; Biesbroek et al., 2013; Glaas and Juhola, 2013). Expanding research on institutional arrangements in at least three key areas can help improve the implementation of adaptation plans in both developed and developing countries: (1) on approaches to improve multilevel institutional coordination between different political and administrative levels in society, with a particular emphasis on balancing a combination of top-down and bottom-up activities (Urwin and Jordan, 2008; Bulkeley et al., 2009; Amundsen et al., 2010; Robinson and Berkes, 2011; Preston et al., 2013); (2) on approaches to overcome the institutional rigidity limiting the horizontal interplay within local governments, where climate adaptation is seen as the isolated task of a singular sector, which hinders the mainstreaming and horizontal coordination across professional sectors and departments and constrains the extent to which systems can learn or adapt to climate change (Bulkeley et al., 2009; Burch, 2010; Dovers and Hezri, 2010; Glaas et al., 2010; Storbjörk, 2010; Juhola and Westerhoff, 2011; Hedensted Lund et al., 2012; Runhaar et al., 2012; Uittenbroek et al., 2012; van den Berg and Coenen, 2012; Wilby and Keenan, 2012); and (3) on approaches improving coordination between formal governmental and administrative agencies and social and private stakeholders in order to create participatory approaches maintaining regard for the highly localized and contextual nature of climate adaptation, and facilitating a collaboration for production of knowledge and interactive learning (Pahl-Wostl, 2009; Engle and Lemos, 2010; Tompkins et al., 2010; Preston et al., 2011; Jonsson et al., 2012; Mees et al., 2012).

The literature illustrates a trend to consider planning a problem-free process capable of delivering positive outcomes for adaptation to climate change. Expanding research seeking to build a better understanding of the limitations and strengths of planning can help avoid underestimating the complexity of adaptation as a social process, and creating unrealistic expectations in societies about the capacity of planning to deliver the intended outcome of adaptation (Repetto, 2008; Biesbroek et al., 2009; Blanco and Alberti, 2009; Dovers, 2009; Berrang-Ford et al., 2011; Juhola and Westerhoff, 2011; Mozumder et al., 2011; Preston et al., 2011; Sanchez-Rodriguez, 2012).

Research efforts considering adaptation planning and implementation as learning processes can help in carrying out periodical adjustments to accommodate changes in climate, socioeconomic conditions, and emergent risks in order to strengthen the role of planning as a societal tool for adaptation (Holden, 2008; Frommer, 2009; Hinkel et al., 2009; Glaas et al., 2010; Hofmann et al., 2011). The literature recognizes monitoring and evaluation as important learning tools in adaptation planning but it also acknowledges both as an under-researched topic (Adger et al., 2009b; Preston et al., 2009; Tompkins et al., 2010; Wolf et al., 2010).

Expanding the research on the metrics to characterize the success of the goals of adaptation, the trade-offs involved, and recognizing the importance of context can help avoid generalized assessments about the contribution of adaptation to managing the risks posed by climate change, and to identify what builds adaptive capacity and what functions as limits and barriers to adaptation (Arnell, 2010; Barnett and Campbell, 2010; Engle, 2011).

Adaptation planning and implementation can benefit from holistic approaches afforded by linking adaptation to development; by coupling adaptive improvements in infrastructure with ecosystem services, governance, and community welfare; by improving community resilience through enhancing local ownership; and by creating organizations able to respond to climate change issues through increased adaptive capacity.

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16

Adaptation Opportunities, Constraints, and Limits

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16

Executive Summary

Risk-based approaches to decision making provide a useful foundation for assessing the potential opportunities, constraints, and limits associated with adaptation of human and natural systems (*medium evidence*, *high agreement*). Risk management frames the consequences of climate change and potential adaptation responses in the context of actors' values, objectives, and planning horizons as they make decisions under uncertainty. Adaptation planning and implementation are therefore contingent on actors' perceptions of risk. Some risks may be routine and/or the consequences so minor that they are accepted. Other risks may be judged intolerable because they pose fundamental threats to actors' objectives or the sustainability of natural systems. A key objective of adaptation is to avoid such intolerable risks. Yet, the capacity of societal actors and natural systems to adapt is finite, and thus there are limits to adaptation. {16.2, 16.3.2, 16.4, Box 16-1}

Understanding of how the adaptive capacity of societal actors and natural systems influences the potential for adaptation to effectively manage climate risk has improved since the Fourth Assessment Report (AR4; *very high confidence*). Adaptive capacity is influenced by actors' abilities to capitalize on available opportunities that ease the planning and implementation of adaptation as well as constraints that make adaptation processes more difficult for both human and natural systems. Opportunities and constraints are unevenly distributed among global regions, communities, sectors, ecological systems, and species as well as across different time periods. Recent studies have provided greater recognition of the role of private businesses in facilitating adaptation. However, much of the current knowledge about adaptation opportunities and constraints is dominated by insights from public institutions and community-based case studies. {16.2-5, Box 16-1}

Opportunities exist to enable adaptation planning and implementation for actors across all sectors and geographic regions (*very high confidence*). Adaptation guidance, information, and tools are increasingly available to practitioners operating in different sectoral, regional, and organizational contexts. Enhancing the awareness of individuals, organizations, and institutions about climate change vulnerability, impacts, and adaptation can help build individual and institutional capacity for adaptation planning and implementation. However, addressing knowledge deficits alone is not sufficient to achieve successful adaptation. The development and provision of tools for risk and vulnerability assessment as well as decision-support tools and early warning systems can help actors prioritize adaptation needs and identify options that reduce vulnerability. Opportunities can also arise as actors learn from experience with climate variability and incorporate consideration for long-term climate change into disaster risk reduction efforts. Formal policies regarding infrastructure design standards or spatial planning can trigger adaptation action. However, many adaptation opportunities arise as ancillary benefits of actions implemented for reasons other than climate change. {16.2, 16.3.1, 16.5; Tables 16-1, 16-3; Boxes 16-1, 16-2, CC-EA}

A range of biophysical, institutional, financial, social, and cultural factors constrain the planning and implementation of adaptation options and potentially reduce their effectiveness (*very high confidence*). Adaptation of both human and natural systems is influenced by the rate of climate change as well as rates of economic development, demographic change, ecosystem alteration, and technological innovation. Adaptation planning and implementation may require significant inputs of knowledge as well as human, social, and financial capital. Real or perceived deficiencies in access to such resources can and do constrain adaptation efforts in both developing and developed nations. Public and private institutions influence the distribution of such resources as well as the development of policies, legal instruments, and other measures that facilitate adaptation. Therefore, institutional weaknesses, lack of coordinated governance, and conflicting objectives among different actors can constrain adaptation. Cultural characteristics including age, gender, and sense of place influence risk perception, entitlements to resources, and choices about adaptation. Societal actors and natural systems may experience multiple constraints that interact. {16.2, 16.3.2, 16.5; Tables 16-2, 16-3; Boxes 16-1, 16-3}

Limits to adaptation can emerge as a result of the interactions among climate change and biophysical and socioeconomic constraints (*medium evidence*, *high agreement*). An adaptation limit occurs owing to the inability to avoid an intolerable risk to an actor's objectives and/or to the sustainability of a natural system. Understanding of limits is informed by historical and recent experience where limits to adaptation have been observed, as well as by limits that are anticipated to arise as a consequence of future global change. Recent studies have provided valuable insights regarding global "tipping points," "key vulnerabilities," or "planetary boundaries" as well as evidence of climate thresholds for agricultural crops, species of fish, forest and coral reef communities, and humans. However, for most regions and sectors, there is a lack of empirical evidence to quantify magnitudes of climate change that would constitute a future adaptation limit. Furthermore, economic

development, technology, and cultural norms and values can change over time to enhance or reduce the capacity of systems to avoid limits. As a consequence, some limits may be considered "soft" in that they may be alleviated over time. Nevertheless, some limits may be "hard" in that there are no reasonable prospects for avoiding intolerable risks. Recent literature suggests that incremental adaptation may not be sufficient to avoid intolerable risks, and therefore transformational adaptation may be required to sustain some human and natural systems. {16.2-7; Table 16-3; Boxes 16-1, 16-4}

Greenhouse gas (GHG) mitigation can reduce the rate and magnitude of future climate change and therefore the likelihood that limits to adaptation will be exceeded (*medium evidence*, *high agreement*). Adaptation and GHG mitigation are complementary risk management strategies. However, residual loss and damage will occur from climate change despite adaptation and mitigation action. Knowledge about limits to adaptation can inform the level and timing of mitigation needed to avoid dangerous anthropogenic interference with the climate system. For example, the level of effort needed to adapt to a 4°C increase in global mean temperature would be significantly greater than that needed to adapt to lower magnitudes of temperature increase. Mitigation can reduce the likelihood of 4°C of warming and therefore the likelihood of exceeding limits to adaptation of natural and human systems. However, the empirical evidence needed to identify limits to adaptation of specific sectors, regions, ecosystems, or species that can be avoided with different GHG mitigation pathways is lacking. {16.3.2.2, 16.6; Box 16-3}

The selection and implementation of specific adaptation options has ethical implications (*very high confidence*). Adaptation decision making involves the reconciliation of legitimate differences about how adaptation resources are distributed and the values that adaptation seeks to protect. For example, the costs and benefits of different adaptation options, such as insurance schemes or large-scale infrastructure projects, may be inequitably distributed among different actors and stakeholders. Such inequities may generate ethical questions regarding who is advantaged or disadvantaged by adaptation actions. In addition, awareness that climate change may exceed the capacity of actors to adapt may have ethical implications for decisions regarding mitigation and climate targets as well as investments in GHG mitigation policies and measures. National and international law as well as decision making at regional and local scales among both public and private actors will influence distributive and procedural justice in adaptation planning and implementation. {16.3.3.8, 16.6-7; Table 16-4; Box 16-4}

Successful adaptation requires not only identifying adaptation options and assessing their costs and benefits, but also exploiting available mechanisms for expanding the adaptive capacity of human and natural systems (*medium evidence*, *high agreement*). Since the AR4, a growing body of literature provides guidance on how enabling conditions for adaptation can be developed and how constraints can be reduced. Continued development of this knowledge through research and practice could accelerate more widespread and successful adaptation outcomes. However, seizing opportunities, overcoming constraints, and avoiding limits can involve complex governance challenges and may necessitate new institutions and institutional arrangements to effectively address multi-actor, multiscale risks. {16.2-3, 16.5, 16.8; Table 16-1; Box CC-EA}

16.1. Introduction and Context

Since the IPCC's Fourth Assessment Report (AR4), demand for knowledge regarding the planning and implementation of adaptation as a strategy for climate risk management has increased significantly (Preston et al., 2011a; Park et al., 2012). This chapter assesses recent literature on the opportunities that create enabling conditions for adaptation as well as the ancillary benefits that may arise from adaptive responses. It also assesses the literature on biophysical and socioeconomic constraints on adaptation and the potential for such constraints to pose limits to adaptation. Given the available evidence of observed and anticipated limits to adaptation, the chapter also discusses the ethical implications of adaptation limits and the literature on system transformational adaptation as a response to adaptation limits.

To facilitate this assessment, this chapter provides an explicit framework for conceptualizing opportunities, constraints, and limits (Section 16.2). In this framework, the core concepts including definitions of adaptation, vulnerability, and adaptive capacity are consistent with those used previously in the AR4 (Adger et al., 2007). However, the material in this chapter should be considered in conjunction with that of complementary WGII AR5 chapters. These include Chapter 14 (Adaptation Needs and Options), Chapter 15 (Adaptation Planning and Implementation), and Chapter 17 (Economics of Adaptation). Material from other WGII AR5 chapters is also relevant to informing adaptation opportunities, constraints, and limits, particularly Chapter 2 (Foundations for Decision Making) and Chapter 19 (Emergent Risks and Key Vulnerabilities). This chapter also synthesizes relevant material from each of the sectoral and regional chapters (Section 16.5).

To enhance its policy relevance, this chapter takes as its entry point the perspective of actors as they consider adaptation response strategies over near, medium, and longer terms (Eisenack and Stecker, 2012; Dow et al., 2013a,b). Actors may be individuals, communities, organizations, corporations, non-governmental organizations (NGOs), governmental agencies, or other entities responding to real or perceived climate-related stresses or opportunities as they pursue their objectives (Patt and Schröter, 2008; Blennow and Persson, 2009; Frank et al., 2011). These actors may seek to navigate near-term constraints to implement adaptation while simultaneously working to alleviate those constraints to enable greater flexibility and adaptive capacity in the future. Therefore, it is necessary to consider diverse time frames for possible social, institutional, technological, and environmental changes. These time frames also differ in the types of uncertainties that are relevant, ranging from those of climate scenarios and models, possible system thresholds, nonlinear responses or irreversible changes in social or environmental systems, and the anticipated magnitude of impacts associated with higher or lower levels of climate change (Meze-Hausken, 2008; Hallegatte, 2009; Briske et al., 2010).

To provide further background and context, this chapter proceeds by revisiting relevant findings on adaptation opportunities, constraints, and limits within the AR4 and the more recent IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) (IPCC, 2012). The chapter then presents a framework for adaptation, opportunities, and limits with an emphasis on explicit definitions of these concepts to facilitate assessment. Key components of this framework are assessed in subsequent chapters, including the synthesis of how these components are treated among the different sectoral and regional chapters of the WGII AR5 report. The chapter subsequently assesses relationships between mitigation and adaptation opportunities, constraints, and limits as well as their ethical implications. The chapter concludes with discussion of key pathways forward for research and practice to seize opportunities, overcome constraints, and avoid limits.

16.1.1. Summary of Relevant AR4 Findings

The AR4 Summary for Policymakers of Working Group II concluded that there are "formidable environmental, economic, informational, social, attitudinal and behavioural barriers to the implementation of adaptation" and that "availability of resources and building adaptive capacity are particularly important" (IPCC, 2007a, p. 19). These findings were based primarily on Chapter 17, Assessment of Adaptation Practices, Options, Constraints and Capacity (Adger et al., 2007). The key conclusion from Adger et al. (2007, p. 719), as relevant to this chapter, was as follows: "There are substantial limits and barriers to adaptation (*very high confidence*)." The authors go on to discuss biophysical and technological limits to adaptation as well as barriers arising from technological, financial, cognitive and behavioral, and social and cultural factors. The authors also noted both significant knowledge gaps and impediments to the sharing of relevant information to alleviate those gaps.

These findings were further evidenced by the sectoral, and particularly regional, chapters of the WGII AR4 report. For example, the chapters assessing impacts and adaptation in Africa, Asia, and Latin America collectively emphasized the significant constraints on adaptation in developing nations. Meanwhile, the chapter on Small Islands by Mimura et al. (2007) identified several constraints to adaptation including limited natural resources and relative isolation. Finally, in the chapter on Polar Regions, Anisimov et al. (2007) noted that indigenous groups have developed resilience through sharing resources in kinship networks that link hunters with office workers, and even in the cash sector of the economy. However, they concluded that such responses may be constrained by social, cultural, economic, and political factors. For all of these regions, adaptation constraints are linked to governance systems and the quality of national institutions as well as limited scientific capacity and ongoing development challenges (e.g., poverty, literacy, and civil and political rights).

The AR4 also provided evidence that constraints on adaptation are not limited to the developing world. For example, Hennessy et al. (2007) reported that while adaptive capacity in Australia and New Zealand has strengthened over time, a number of constraints remain including access to tools and methods for impact assessment as well as appraisal and evaluation of adaptation options. They also note weak linkages among the various strata of government regarding adaptation policy and skepticism among some populations toward climate change science. For North America, Field et al. (2007) identify a range of social and cultural barriers, informational and technological barriers, and financial and market barriers. The chapter on Europe mentions the limits faced by species and ecosystems due to lack of migration space, low soil fertility, and human alterations of the landscape (Alcamo et al., 2007).

Several other AR4 chapters assessed literature relevant to this chapter. Chapter 18, Inter-Relationships between Adaptation and Mitigation (Klein et al., 2007), discussed the possible effect of mitigation on adaptation (an issue also considered by WGIII AR4, in particular by Fisher et al. (2007) and Sathaye et al. (2007)). Finally, Chapter 19, Assessing Key Vulnerabilities and the Risk from Climate Change (Schneider et al., 2007), outlined how the presence of adaptation constraints and limits is a contributing factor to vulnerability. Chapters that address similar themes also appear in the AR5, and cross-references are provided in this chapter to this more recent material.

16.1.2. Summary of Relevant SREX Findings

The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) assesses a broad array of literature on climate change, extreme events, adaptation, and disaster risk reduction. A central framing concept for the SREX was the assertion that (Lavell et al., 2012, p. 37), " . .while there is a long-standing awareness of the role of development policy and practice in shaping disaster risk, advances in the reduction of the underlying causes – the social, political, economic, and environmental drivers of disaster risk – remain insufficient to reduce hazard, exposure, and vulnerability in many regions (UNISDR, 2009, 2011) (*high confidence*)."

This summary of relevant SREX material focuses on how the key findings of the SREX provide insights relevant to the treatment of opportunities, constraints, and limits in this chapter.

With respect to opportunities, the linkages between development and disaster risk reduction provide a number of avenues for enhancing societal resilience to natural disasters and climate change. For example, the SREX highlights the benefits of considering disaster risk in national development planning if strategies to adapt to climate change are adopted (Lal et al., 2012). The observed dependence of disasters on underlying patterns of development is indicative of the opportunities for increasing societal resilience through sustainable development. In addition, incorporating adaptation into multi-hazard risk management may be an effective strategy for the efficient integrated management of natural hazards and future climate risk (O'Brien et al., 2012).

The SREX report also discussed the constraints associated with enhancing disaster risk reduction and climate adaptation. In particular, ongoing development deficits as well as inequality in coping and adaptive capacities pose fundamental constraints (Cardona et al., 2012). The SREX noted that national systems and institutions are critical for generating the capacity needed to manage the risks associated with climate variability and change (Lal et al., 2012). Yet capacity at one level of governance does not necessarily convey capacity to other levels (Burton et al., 2012). Even in the presence of robust institutions, rates of socioeconomic and climate change can interact to constrain adaptation. For example, O'Brien et al. (2012) note that rapid socioeconomic development in vulnerable urban areas can increase societal exposure to natural hazards while simultaneously constraining the capacity of actors to implement policies and measures to reduce vulnerability. Overcoming these constraints to achieve development objectives is constrained by a paucity of disaster data at the local level as well as persistent uncertainties regarding the manifestation of extreme events in future decades (Cutter et al., 2012; Seneviratne et al., 2012).

The SREX report cautioned that natural hazards, climate change, and societal vulnerability can pose fundamental limits to sustainable development. Such limits can arise from the exceedance of natural and/or societal thresholds or tipping points (Lal et al., 2012; O'Brien et al., 2012; Seneviratne et al., 2012). Accordingly, the SREX concludes that adaptation options should include not only incremental adjustments to climate variability and climate change, but also transformational changes that alter the fundamental attributes of systems. Though challenging to implement, such transformation may be aided by actors questioning prevailing assumptions, paradigms, and management objectives toward the development of new ways of managing risk and identifying opportunities (O'Brien et al., 2012).

16.2. A Risk-Based Framework for Assessing Adaptation Opportunities, Constraints, and Limits

Risk is an intrinsic element of any understanding of "*dangerous anthropogenic interference with the climate system*" (UNFCCC, 1992) and associated assumptions about the capacity of human and natural systems to adapt to climatic change. The United Nations Framework Convention on Climate Change (UNFCCC) refers specifically to adaptation of ecosystems, threats to food production, and sustainable economic development. While there is evidence of opportunities in natural and human systems to adapt to climate changes, there is also evidence that the potential to adapt is constrained, or more difficult, in some situations, and faces limits in others (*very high confidence*; e.g., Adger et al., 2009; Dow et al., 2013a,b; see also Sections 16.3-5).

This chapter applies a risk-based framework and a set of linked definitions to the assessment of adaptation opportunities, constraints, and limits. This approach is consistent with other risk management approaches to guiding adaptation responses to climate change (IPCC, 2012; see also Sections 1.3.4, 2.1.2, 14.4, 15.3). The adaptation literature ascribes a number of different meanings to the terms opportunities, constraints, and limits, which may have added confusion to an important scientific and policy debate. The AR4, for example, provided a specific definition of adaptation limits, but used the terms barriers and constraints interchangeably to describe general impediments to adaptation (Adger et al., 2007). Similar ambiguities are apparent within the rapidly expanding literature focused on adaptation constraints (Biesbroek et al., 2013a).

The framework and definitions employed here draw on a number of literatures (Dow et al., 2013a,b), in particular vulnerability assessment (Füssel, 2006; Füssel and Klein, 2006) and risk assessment (Jones, 2001; Klinke and Renn, 2002; Renn, 2008; National Research Council, 2010) as well as climate adaptation (Hulme et al., 2007; Adger et al., 2009; Hall et al., 2012). Moving from such general definitions to applications requires specifying who or what is adapting, what they are adapting to, and the process of adaptation (Smit et al., 1999). Hence, this chapter explores adaptation opportunities, constraints, and limits from the context of social actors, which includes individuals, businesses, government agencies, or informal social groups.

Frequently Asked Questions

FAQ 16.1 | What is the difference between an adaptation barrier, constraint, obstacle, and limit?

An adaptation constraint represents a factor or process that makes adaptation planning and implementation more difficult. This could include reductions in the range of adaptation options that can be implemented, increases in the costs of implementation, or reduced efficacy of selected options with respect to achieving adaptation objectives. In this context, a constraint is synonymous with the terms adaptation barrier or obstacle that also appear in the adaptation literature. However, the existence of a constraint alone does not mean that adaptation is not possible or that one's objectives cannot be achieved. In contrast, an adaptation limit is more restrictive in that it means there are no adaptation options that can be implemented over a given time horizon to achieve one or more management objectives, maintain values, or sustain natural systems. This implies that certain objectives, practices, or livelihoods as well as natural systems may not be sustainable in a changing climate, resulting in deliberate or involuntary system transformations.

An explicit focus on risk is particularly useful to understanding climate adaptation (Jones and Preston, 2011; Dow et al., 2012b). Adaptation is intended to reduce the risk to assets or systems of value (Adger et al., 2012b). The concept of risk integrates the dimensions of probability and uncertainty with the material and normative dimensions that shape societal responses to threats (Renn, 2008). Figure 16-1 relates judgments about risk and the ability to maintain risks at a tolerable level to the concept of adaptation and adaptation opportunities, constraints, and limits (Box 16-1). Drawing on the work of Klinke and Renn (2002), actors evaluate risks based on one of three categories: acceptable, tolerable, and intolerable. Acceptable risks are those deemed so low that additional efforts at risk reduction, in this case climate adaptation efforts, are not justified. Tolerable risks relate to situations where adaptive risk management efforts are required and effective for risks to be kept within reasonable levels. The scope of risks that fall within the tolerable area is influenced by adaptation opportunities and constraints. Therefore, the categorization of risks varies across spatial, jurisdictional, and temporal. As discussed later in this chapter, opportunities and constraints may be physical, technological, economic, institutional, legal, cultural, or environmental in nature (Sections 16.3, 16.5-7). Constraints may limit the range of available adaptation options creating the potential for residual damages for actors, species, or ecosystems associated with specific regions or sectors. Under some circumstances, the risk of residual damage may be viewed as an acceptable or tolerable trade-off (Stern et al., 2006; de Bruin et al., 2009a).

Intolerable risks may be related to threats to core social objectives associated with health, welfare, security, or sustainability (Klinke and Renn, 2002; Renn, 2008; Dow et al., 2013a,b). Risks become intolerable when practicable or affordable adaptation options to avoid escalating risks to such valued objectives or biophysical needs become unavailable. Therefore, a limit is a point when an intolerable risk must be accepted; the objective itself must be relinquished; or some adaptive transformation must take place to avoid intolerable risk. Such a discontinuity may take several forms such as individual's decision to relocate, an insurance company's decision to withdraw coverage, or a species' extinction. The alternative to such discontinuities is an escalating and unmediated risk of losses (Moser and Ekstrom, 2010; see also Section 16.4.2). While individuals have their own perspectives about what are acceptable, tolerable, or intolerable risks, collective judgments about risk are also codified through mechanisms such as engineering design standards, air and water quality standards, and legislation that establishes goals for regulatory action. There are also international agreements that establish norms and rights relevant to climate change risks (Knox, 2009; OHCHR, 2009; Crowley, 2011), such as the Universal Declaration of Human Rights, the International Covenant on Civil and Political Rights, and the International Covenant on Economic, Social and Cultural Rights. Further, these high level responses often shape the constraints and opportunities to adaptation and responses to risk at lower levels through the distribution

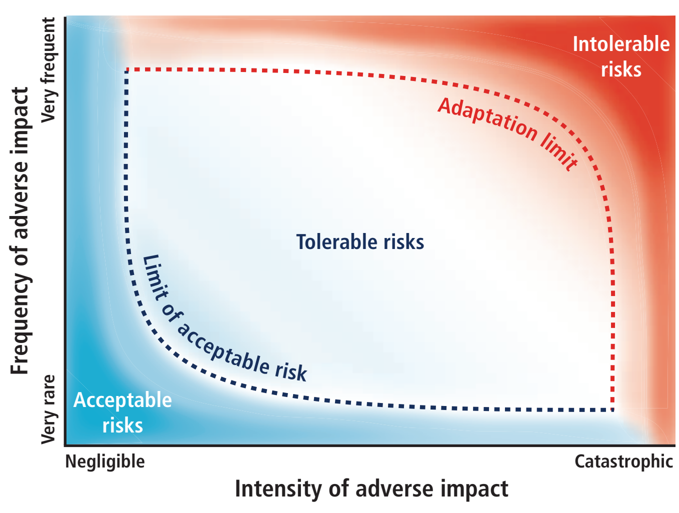

Figure 16-1 | Conceptual model of the determinants of acceptable, tolerable, and intolerable risks and their implications for limits to adaptation (Dow et al., 2013b, based on Klinke and Renn, 2002; see also Renn and Klinke, 2013). In this conceptual diagram, adaptation efforts are seen as keeping risks to objectives within the tolerable risk space. Opportunities and constraints influence the capacity of actors to maintain risks within a tolerable range. The dotted lines indicate that individual or collective views on risk tolerance with respect to the frequency and intensity of climate-related risks are not fixed, but may vary and change over time. In addition, the shape or angle of the lines and the relative area in each section of the diagram are illustrative and may themselves change as capacities and attitudes change. The shaded areas represent the potential differences in perspective among actors.

Box 16-1 | Definitions of Adaptation Opportunities, Constraints, and Limits

Adaptation Opportunities: *Factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits*. These factors enhance the ability of an actor(s) to secure their existing objectives, or for a natural system to retain productivity or functioning. For instance, increased public awareness and support for adaptation, availability of additional resources from actors at other levels of governance to overcome constraints and soft limits, and interest in acquiring co-benefits arising from adaptation strategies can all facilitate adaptation planning and implementation. Private sector efforts in research and development that can improve affordability, flexibility, or ease of implementation could also create opportunities (Section 14.2.4). Such adaptation opportunities, sometimes also referred to as adaptation enablers, are distinct from opportunities arising from climate change (e.g., longer growing seasons), which are commonly referred to as potential benefits of climate change or adaptation options.

Adaptation Constraints: *Factors that make it harder to plan and implement adaptation actions*. Adaptation constraints restrict the variety and effectiveness of options for actors to secure their existing objectives, or for a natural system to change in ways that maintain productivity or functioning. These constraints commonly include lack of resources (e.g., funding, technology, or knowledge) (Section 16.3.2), institutional characteristics that impede action (Section 16.3.2.8), or lack of connectivity and environmental quality for ecosystems (Section 4.4). The terms "barriers" and "obstacles" are frequently used as synonyms. Constraints—alone or in combination—can drive an actor or natural system to an adaptation limit.

Adaptation Limit: *The point at which an actor's objectives or system's needs cannot be secured from intolerable risks through adaptive actions* (Adger et al., 2009; Moser and Ekstrom, 2010; Dow et al., 2013a,b; Islam et al., 2014).

Hard Adaptation Limit: No adaptive actions are possible to avoid intolerable risks.
Soft Adaptation Limit: Options are currently not available to avoid intolerable risks through adaptive action.

A limit to adaptation means that, for a particular actor, system, and planning horizon of interest, no adaptation options exist, or an unacceptable measure of adaptive effort is required, to maintain societal objectives or the sustainability of a natural system. Objectives include, for example, maintaining safety standards such as those codified in laws, regulations, or engineering design standards (e.g., 1-in-500 year levees); security of air or water quality; as well as equity, cultural cohesion, and preservation of livelihoods. Requirements for sustaining natural systems might include temperature ranges or moisture availability. In the case of hard limits, no adaptation options are foreseeable, even when looking beyond the current planning horizon. For soft limits, however, adaptation options could become available in the future owing to changing attitudes or values or as a result of innovation or other resources becoming available to an actor. For example, 31 Native Alaskan villages are facing "imminent threats" due to coastal erosion and at least 12 of the 31 have begun to explore relocation or have decided to partially or totally relocate (US GAO, 2009). In the case of these communities with minimum local revenue, the ability to relocate depends on the political and financial support of the U.S. federal government (Huntingon et al., 2012). Therefore, limits are strongly influenced by relationships among public and private actors and institutions across different spatial, temporal, and jurisdictional scales (Cash et al., 2006; see also Section 16.4.1).

of resources, institutional design, and support of capacity development (Sections 16.2-3, 16.4.1). If these risks and discontinuities have global-scale consequences, they can be linked to "key vulnerabilities" to climate change (Section 19.6). Consistent with our framing of adaptation limits, such key vulnerabilities would need to be assessed in terms of the limits they imply for specific social actors, species, and ecosystems.

It is essential to evaluate opportunities, constraints, and limits with respect to both the rate and magnitude of climate change and the relevant time horizon for an actor, a species, or an ecosystem. Opportunities, constraints, and limits to adaptation develop along a dynamic continuum (i.e., the dotted lines in Figure 16-1 can shift), together conditioning the capacity of natural and human systems to adapt to climate change. New opportunities for adaptation may emerge through time; constraints may be loosened; and some, although not all, limits that arise in the present may eventually be shifted or removed altogether. For a given social actor, the time horizon for adaptation decisions usefully bounds an analysis of opportunities, constraints, and limits. For natural systems, the rate of species responses relative to changes in environmental conditions is a limit to the capacity to adapt (Sections 4.3.2.5, 4.4, 16.3.2.3, 16.4.1). The observed rate of evolutionary and other species responses ranges from rapid to inadequate to allow persistence (Hoffmann and Sgro, 2011).

Because adaptation limits relate to adaptation resources and attitudes to risk that may change over time, some limits may be viewed as "soft" or time sensitive (Section 16.4.1). While a given adaptation option may not be available today or require impracticable levels of effort, it may become available through innovation or changes in attitudes in time. Soft limits may be shifted by investments in research and development, changes in regulatory rules or funding arrangements, or by changing social or political attitudes (Park et al., 2012; Adger et al., 2013). Other limits are "hard" or time insensitive in that there is no known process to change them (Section 16.4.1). Examples of hard limits include water supply in fossil aquifers, limits to retreat on islands, and loss of genetic diversity.

16.3. Adaptation Opportunities and Constraints

Different actors, sectors, and geographic regions have differential capacities to adapt to climate variability and change (*very high confidence*; Adger et al., 2007; IPCC, 2012), although those capacities can be difficult to measure (Tol et al., 2008; Hinkel, 2011). Since the AR4 (Adger et al., 2007), the literature on the factors that contribute to adaptive capacity has deepened (Adger et al., 2009; Moser and Ekstrom, 2010). This literature has evolved along two different pathways. One focuses on the range of opportunities that exist to facilitate adaptation planning and implementation. The other, which is also more extensive, focuses on describing the constraints that inhibit adaptation. Although they are sometimes treated in the literature as distinct, opportunities and constraints are complementary in that adaptive capacity is influenced jointly by the extent to which actors take advantage of available opportunities to pursue adaptation responses and the extent to which those actors or natural, unmanaged systems experience constraints. In addition, factors that are identified as constraints may also reveal valuable opportunities for adaptation interventions to build adaptive capacity.

While some level of generalization regarding opportunities and constraints that are common to different regions, sectors, communities, and actors is possible, the manner in which they manifest is context dependent (*very high confidence*; Adger et al., 2007; Orlove, 2009; Kasperson and Berberian, 2011; Weichselgartner and Breviere, 2011; IPCC, 2012). For example, actors that frame adaptation as a process of capacity building or sustainable development may pursue different adaptation options with different opportunities and constraints compared with those that frame adaptation as largely addressing climate change impacts (McGray et al., 2007; Fünfgeld and McEvoy, 2011). Adaptation researchers apply their own frameworks and heuristics that influence understanding of adaptation processes (Biesbroek et al., 2013b; Preston et al., 2013b). Therefore, one must be cautious in applying generic assumptions regarding adaptation opportunities and constraints in assessments of vulnerability and adaptive capacity or in the identification of appropriate adaptation responses (Adger and Barnett, 2009; Barnett and Campbell, 2009; Mortreux and Barnett, 2009). The recent adaptation literature suggests significant work remains in understanding such context-specific determinants of vulnerability and adaptive capacity and in effectively using the knowledge gained from available case studies to facilitate adaptation more broadly (Tol and Yohe, 2007; Klein, 2009; Smith et al., 2010; Hinkel, 2011; Preston et al., 2011b; Biesbroek et al., 2013a). Therefore, the discussion of opportunities and constraints here should be considered in the context of the sectoral and regional synthesis (Section 16.5) as well as the sector- and region-specific material on constraints and opportunities in other WGII AR5 chapters.

16.3.1. Adaptation Opportunities

16.3.1.1. Enabling Conditions for Adaptation

Adaptation opportunities represent enabling factors that enhance the potential for actors to plan and implement actions to achieve their

Frequently Asked Questions

FAQ 16.2 | What opportunities are available to facilitate adaptation?

Although an extensive literature now exists regarding factors that can constrain adaptation, there is *very high confidence* that a broad range of opportunities exist for actors in different regions and sectors that can ease adaptation planning and implementation. Generally, sustainable economic development is an overarching process that can facilitate adaptation, and therefore represents a key opportunity to reduce adaptation constraints and limits. More specifically, those actions or processes that enhance the awareness of adaptation actors and relevant stakeholders and/or enhance their entitlements to resources can expand the range of adaptation options that can be implemented and help overcome constraints. The development and application of tools to support assessment, planning, and implementation can aid actors in weighing different options and their costs and benefits. Policies, whether formal policies of government institutions, initiatives of informal actors, or corporate policies and standards, can direct resources to adaptation and/or reduce vulnerability to current and future climate. Finally, the ability for humans to learn from experience and to develop new practices and technologies through innovation can significantly expand adaptive capacity in the future.

Table 16-1 | Identification of key adaptation opportunities. Each type of opportunity is represented by multiple illustrative examples as well as supporting references.

Opportunity	Examples	References
Awareness raising	Positive stakeholder engagement	O'Neill and Chicholson-Cole (2009); Kahan (2010)
	Communication of risk and uncertainty	Berry et al. (2011); Pidgeon and FIschhoff (2011); Pidgeon (2012); Lieske et al. (2013)
	Participatory research	Pearce et al. (2009); McNamara and McNamara (2011); Sheppard et al. (2011); Duru et al. (2012); Faysse et al. (2012)
Capacity building	Research, data, education, and training	PCAST (2011); WMO (2011); Bangay and Blum (2012); Lemos et al. (2013)
	Extensions services for agriculture	Deressa et al. (2009); Fosu-Mensah et al. (2012)
	Resource provision	Ayers (2009); Ayers and Huq (2009); Grasso (2010); Klein (2010); Rübbelke (2011)
	Development of human capital	Bowen et al. (2012); Lemos et al. (2013)
	Development of social capital	Deressa et al. (2009); Adger et al. (2010); Engle and Lemos (2010); Huang et al. (2011)
Tools	Risk analysis	van Aalst et al. (2008); Pidgeon and Butler (2009); Chin et al. (2010); Zhou et al. (2012); Wade et al. (2013)
	Vulnerability assessment	Allison et al. (2009); Moreno and Becken (2009); Nelson et al. (2010b); Romieu et al. (2010); Koh (2011); Preston et al. (2011b)
	Multi-criteria analysis	de Bruin et al. (2009b); Garfi et al. (2011); Yang et al. (2012); Kyung-Soo et al. (2013)
	Cost/benefit analysis	Tol et al. (2008); Hallegatte (2009); Weitzman (2009); Mechler and Islam (2013)
	Decision support systems	Norman et al. (2010); Wenkel et al. (2013)
	Early warning systems	Lowe et al. (2011); Lenton (2013); Marvin et al. (2013)
Policy	Integrated resource and infrastructure planning	Rosenberg et al. (2010); Becker et al. (2012); Heeres et al. (2012)
	Spatial planning	Brown (2011); Wheeler (2012); Pinto et al. (2013)
	Design/planning standards	Hamin and Gurran (2009); Mailhot and Duchesn (2009); Kwok and Rajkovich (2010); Ren et al. (2011); Nassopoulos et al. (2012)
Learning	Experience with climate vulnerability and disaster risk	Fiksel (2006); Crespo Cuaresma et al. (2008); Cutter et al. (2012)
	Learning-by-doing	Berkhout et al. (2006); Bulkeley and Castán Broto (2012); Roberts et al. (2012)
	Monitoring and evaluation	GIZ (2011a,b); Preston et al. (2011a); Adaptation Sub-Committee (2012)
Innovation	Technological change	Hanjra and Qureshi (2010); Chhetri et al. (2012); Lybbert and Sumner (2012); Rodima-Taylor et al. (2012); Vermeulen et al. (2012)
	Infrastructure efficiencies	Beard et al. (2009); Newton (2013)
	Digital/mobile telecommunications	Ospina and Heeks (2010a,b); Meera et al. (2012)

adaptation objective(s) or facilitate adaptive responses by natural systems to climate risk (Box 16-1). Therefore, an opportunity is distinct from an adaptation option, which is a specific means of achieving an adaptation objective (such as an early warning system as a means of reducing vulnerability to tropical cyclones) or a strategy for the conservation of an ecological system (Section 14.3; Table 14-1). Adaptation opportunities described here also do not consider the potential beneficial consequences of climate change (Box 16-1), an issue addressed to varying degrees among the various sectoral and regional chapters.

Opportunities for adaptation range from increasing awareness of climate change, its consequences, and the potential costs and benefits of adaptation options to the implementation of specific policies that create conditions that are conducive to adaptation implementation. For example, rice is a key food crop, particularly in Asia, in which 90% of rice is produced and subsequently consumed (Timmer, 2010). Multiple studies have identified rice as being particularly vulnerable to the effects of climate change, including both temperature and water availability impacts (Papademetriou et al., 2000). Therefore, planning and implementation of adaptive responses will be an important component of managing the risk of climate change to rice production (Howden et al., 2007; Lobell et al., 2008; Tilman et al., 2011; Anwar et al., 2013). A range of opportunities are available to support adaptation (Tables 16-1, 16-3) (*very high confidence*). Hypothetically, these could include the use of analysis tools to better understand vulnerabilities and thresholds in rice and develop scenarios of future consequences. That information could then be communicated to farmers, national governments, and international agencies to increase awareness of potential risks. Policies can be used to incentivize adaptation including investments in biotechnology research to breed more resistant strains as well as field studies to identify potential new regions that might be appropriate for rice cultivation in the future.

Such opportunities exist for other agricultural commodities as well as other sectors and regions at risk from climate change (Box 16-2). For example, there is growing recognition of the potential for using disaster response and recovery processes as a means of increasing resilience to future extreme events (Lavell et al., 2012). Meanwhile, case studies of Australian local governments as well as Inuit communities in the Arctic have identified a range of opportunities for building adaptive capacity and overcoming constraints (Smith et al., 2008; Ford, 2009; Ford et al., 2010). These include risk assessment, partnerships, establishment of monitoring and evaluation frameworks, developing finance mechanisms, and formal adaptation policy development.

Sustainable economic development is a critical foundation for the creation of adaptation opportunities (Sections 20.2, 20.6), because it has the potential to build the capacity of individuals and organizations to adapt (*very high confidence*). Sustainable development is associated with increasing opportunities for research, training, and education as

Box 16-2 | A Case Study of Opportunities for Adaptation and Disaster Risk Reduction

Bangladesh has been identified as a region of South Asia that is particularly vulnerable to tropical cyclones (Ali, 1999; Mallick and Rahman, 2013), and this vulnerability is projected to increase due to climate change (Karim and Mimura, 2008; Dasgupta et al., 2010). The nation's response to this vulnerability illustrates the manner in which multiple opportunities can converge to facilitate adaptation and disaster risk reduction. The Cyclone Preparedness Program (CPP) was launched in the 1960s to establish a warning system in coastal regions (Habib et al., 2012). The CPP has been continually improved in subsequent years with assistance from the International Federation of Red Cross and Red Crescent Societies and the International Foundation (Mallick and Rahman, 2013). A coastal reforestation program was also established in the 1960s to enhance natural buffers to storm surge (Mallick and Rahman, 2013; Box CC-EA). The Bangladesh Government initiated construction of cyclone shelters in the late 1980s, yet a cyclone in 1991 revealed that too few shelters were available (Bern et al., 1991; Chowdhury et al., 1993). This prompted collaboration between the government of Bangladesh, the United Nations Development Programme, and the World Bank to launch the Multipurpose Cyclone Shelter Program. That program characterized shelter needs along the coast and provided resources for their construction. In addition, shelter construction, which was concentrated around primary and secondary schools, coincided with national legislation requiring compulsory attendance in primary school, which required the construction of new schools. This created the opportunity for multi-purpose construction of buildings, reflecting the potential ancillary benefits that can arise from integrated planning (Section 16.3.1.2).

More recently, Bangladesh has begun to focus on increasing the resilience of the built environment. This effort has focused on the development of disaster-resilient habitat (Mallick and Rahman, 2007), where communities participate in the design and construction of resilient housing with support from international donors (Mallick et al., 2008; Mallick and Rahman, 2013). This may be a more cost-effective strategy for both reducing mortality and property damage (Mallick et al., 2008). The observed progress in reducing vulnerability to tropical cyclones is a function of various opportunities (awareness, assessment, policies, innovation, and capacity building) that have emerged over the past several decades that created conditions that enabled the implementation of specific policies, projects, and programs. Nevertheless, the additional risk posed by future climate change may necessitate further future investments (Dasgupta et al., 2010).

well as for enhancing access to expertise and tools for assessment activities and decision support. It also increases access to technologies that can enhance efficiencies. For example, water use in the USA has remained relatively constant since the mid-1980s, despite population growth, increases in agricultural yields, and expansion of electricity generation (Kenny et al., 2009). Improvements in technology and management practice stimulated by innovation, education, and learning have increased water use efficiency. This phenomenon may increase the resilience of U.S. water resources to climate change. Yet, these advances are a function of broader national and regional economic development trends. Therefore, future development pathways may have a significant influence on the opportunities for adaptation and therefore the adaptive capacity of adaptation actors (Sections 16.3.2.10, 20.6; Box 16-3).

16.3.1.2. Ancillary Benefits of Adaptation

Some adaptation options may offer ancillary benefits (or co-benefits) independent of their direct benefits with respect to reducing vulnerability to climate change (*very high confidence*; Section 17.2.3). The potential for ancillary benefits has two important implications for adaptation planning and implementation. First, their consideration may result in a more favorable assessment of the cost-effectiveness of a specific adaptation option (Hallegatte, 2009). Second, consideration of the ancillary benefits of adaptation may help in efficiently integrating adaptation into existing management and decision-making processes (Ahmed and Fajber, 2009; Dovers, 2010).

Such ancillary benefits may arise from adaptation responses in three ways:

- *Stimulating adaptation to current climate variability*: Although it is generally assumed that physical, ecological, and social systems are well adapted to current climatic conditions, this is frequently not the case (Dugmore et al., 2009; Heyd and Brooks, 2009). Increased awareness of the potential impacts of future climate change may, in some instances, lead to the implementation of adaptation options to reduce vulnerability or capitalize on opportunities (*medium evidence*, *high agreement*; Section 16.3.2.1).These options may have near-term ancillary benefits with respect to reducing vulnerability to current climate variability and extreme weather events (Füssel, 2008; Hallegatte, 2009; Ford et al., 2010). On the other hand, future reductions in vulnerability to climate change can be perceived as ancillary benefits of near-term responses to current climate variability and natural disasters (Ziervogel et al., 2010a,b). Hence, there may be some ambiguity with respect to what actors perceive as the primary versus ancillary benefit of a particular policy or measure.

- *Generation of climate adaptation goods and services*: Adaptation planning and implementation often may require additional knowledge and investment of resources. Adaptation therefore represents a potential economic opportunity for producers of goods and services used to satisfy adaptation needs (*limited evidence*, *medium agreement*; EBI, 2013). Such services range from vulnerability assessment and risk analysis to the implementation of technology and engineering solutions. The Stern Review indicated that the market opportunities for new infrastructure and buildings resilient to climate change in Organisation for Economic Co-operation and Development (OECD) countries could be quite significant (Stern et al., 2006). For example, the market for snow machines will be influenced by growing concerns about snow cover in more marginal ski resorts (Scott et al., 2006). Higher elevation regions may see new opportunities as a result of snow resort shifts (Bark et al., 2010). Likewise, increased risks associated with track buckling caused by higher summer temperatures may trigger innovation and investment in new railway track and drainage systems (Bark et al., 2010). Rising damage caused by climate change could provide new markets for innovative insurance products and other risk-based financial services (*limited evidence*, *medium agreement*; Botzen et al., 2009, 2010). However, these ancillary benefits must be weighed against the adverse impacts that create the market for such services.
- *Advancing sustainable development*: As part of a larger portfolio of policies and measures, adaptation can assist in addressing existing development deficits while also meeting long-term sustainable development objectives (*very high confidence*; Sections 20.2, 20.6). For example, policy options related to management of water and natural resources under a changing climate; the development of water, transportation, and communication infrastructure; and the promotion of credit and insurance services can promote economic development, increase adaptive capacity, and reduce the impacts of climate change on the poor (Hertel and Rosch, 2010). Therefore, effective adaptation and climate risk management may be important enablers of sustainable economic development.

16.3.2. Adaptation Constraints

As discussed in the AR4 (Adger et al., 2007), a number of factors constrain planning and implementation of adaptation options (*very high confidence*). More recent studies have documented an expanded range of constraints in a diverse array of contexts, but Biesbroek et al. (2013a) note that there is no consensus definition of constraints or a consistent framework for their assessment. Although constraints are often discussed in the literature as discrete determinants of adaptive capacity, they rarely act in isolation (Dryden-Cripton et al., 2007; Smith et al., 2008; Moser and Ekstrom, 2010; Shen et al., 2011). Rather actors are challenged to navigate multiple, interacting constraints in order to achieve a given adaptation objective (*very high confidence*; Adger et al., 2007, 2009; Dryden-Cripton et al., 2007; Shen et al., 2008, 2011; Smith et al., 2008; Jantarasami et al., 2010; Moser and Ekstrom, 2010; see also Section 16.3.2.10). Multiple constraints can significantly reduce the range of adaptation options and opportunities available to actors and therefore may pose fundamental limits to adaptation (*very high confidence*; Section 16.4) and/or drive actors toward responses that may be maladaptive (*limited evidence*, *medium agreement*; Barnett and O'Neill, 2010; Eriksen et al., 2011).

16.3.2.1. Knowledge, Awareness, and Technology Constraints

The AR4 concluded that there are significant knowledge gaps and impediments to flows of information that can constrain adaptation, but knowledge in itself is not sufficient to drive adaptive responses (Adger et al., 2007). These conclusions are echoed by more recent literature. Adaptation practitioners and stakeholders in both developed (Tribbia and Moser, 2008; Gardner et al., 2010; Jantarasami et al., 2010; Ford et al., 2011; Milfont, 2012) and developing nations (Bryan et al., 2009; Deressa et al., 2009; Begum and Pereira, 2013; Pasquini et al., 2013) continue to identify knowledge deficits as an adaptation constraint (*very high confidence*). Often this demand for more information is linked to concerns regarding decision making under uncertainty about the future (*medium evidence*, *medium agreement*; Tribbia and Moser, 2008; Moser, 2010a; Whitmarsh, 2011; Stoutenborough and Vedlitz, 2013). A broad range of guidance on adaptation planning and implementation continues to emerge as a means of empowering actors to pursue adaptation efforts (Clar et al., 2013; EC, 2013; FAO, 2013; USCTI, 2013; Webb and Beh, 2013), and the World Meteorological Organization has emphasized the importance of climate services for vulnerability and disaster risk reduction (WMO, 2011).

A number of recent studies have investigated the extent to which education and knowledge about climate change influences perceptions of risk (Hamilton, 2011; McCright and Dunlap, 2011; Milfont, 2012). For example, studies suggest overconfidence in the ability of actors to manage risk (Wolf et al., 2010; Kuruppu and Liverman, 2011) or differences in the perception of climate risk between actors and governing institutions (Patt and Schröter, 2008a) can constrain adaptation (*medium evidence*, *medium agreement*). Therefore, capacity building through education, training, and information access represents a valuable opportunity for adaptation (Section 16.3.1.1).

Nevertheless, numerous recent studies caution that addressing knowledge deficits may not necessarily lead to adaptive responses (*very high confidence*; Kellstedt et al., 2008; Tribbia and Moser, 2008; Adger et al., 2009; Malka and Krosnick, 2009; Moser, 2010b; Preston et al., 2011b; Kahan et al., 2012; Lemos et al., 2012). Research from the USA indicates that those most informed about science and climate change are not necessarily the most concerned about its potential consequences (Kellstedt et al., 2008; Kahan et al., 2012), although these findings run counter to research from New Zealand, where increased knowledge translated into increased public concern and efficacy (Milfont, 2012). Recent research also indicates that multiple factors influence how knowledge is perceived including political affiliation (Hamilton, 2011; McCright and Dunlap, 2011), educational attainment (McCright and Dunlap, 2011), and the confidence placed on different information sources (Sundblad et al., 2009). Various studies have questioned a common assumption in the climate change literature that improvements in climate information are needed to facilitate adaptation

Box 16-3 | Rates of Change as a Cross-Cutting Constraint

Future rates of global change will have a significant influence on the demand for, and costs of, adaptation (*very high confidence*). Since the AR4, new research has confirmed the commitment of the Earth system to future warming (Lowe et al., 2009; Armour and Roe, 2011; WGI AR5 Section 12.5) and elucidated a broad range of tipping points or "key vulnerabilities" that would result in significant adverse consequences should they be exceeded (Lenton et al., 2008; Rockstrom et al., 2009; see also Chapter 19). While the specific rate of climate change to which different ecological communities or individual species can adapt remains uncertain (Sections 16.3.2.3, 16.4.1), more rapid rates of change can constrain adaptation of natural systems (Hoegh-Guldberg, 2008; Gilman et al., 2008; Maynard et al., 2008; CCSP, 2009; Hallegatte, 2009; Malhi et al., 2009a,b; Thackeray et al., 2010; Lemieux et al., 2011; Fankhauser and Soare, 2013; see also Sections 4.3.2.5, 5.5.6), particularly in the presence of other environmental pressures (*very high confidence*; Brook et al., 2008). Literature suggests that the near-term economic costs of societal adaptation may be substantial, and those costs increase incrementally over time as the climate changes (Section 17.4.4). Therefore, higher rates or magnitudes of climate change may reduce the effectiveness of some adaptation options, and higher costs for adaptation may be incurred (New et al., 2011; Stafford Smith et al., 2011; Peters et al., 2013; see also Section 16.6). However, more rapid rates of change may also create greater incentives for adaptation, resulting in a faster pace of implementation (Travis and Huisenga, 2013).

Although rapid socioeconomic change, including economic development and technological innovation and diffusion, can enhance adaptive capacity (Section 16.3.1), it can also pose constraints (*very high confidence*; Section 20.3.2). Globally, economic losses from climate extremes are doubling approximately every 1 to 2 decades owing to increasing economic exposure (Pielke Jr. et al., 2008; Baldassarre et al., 2010; Bouwer, 2011; Gall et al., 2011; Munich Re, 2011; IPCC, 2012; Preston, 2013). Such losses are associated with high interannual variability (Preston, 2013), but current trends are projected to continue in future decades (Pielke Jr., 2007; Montgomery, 2008; O'Neill et al., 2010; UN DESA Population Division, 2011; Preston, 2013; see also Section 10.7.3), although losses may decline relative to growth in gross domestic product (GDP; IPCC, 2012). In addition, population growth and economic development can lead to greater resource consumption and ecological degradation (Alberti, 2010; Chen et al., 2010; Raudsepp-Hearne et al., 2010; Liu et al., 2012), which can constrain adaptation in regions where livelihoods are closely linked to ecosystem goods and services (*very high confidence*; Badjeck et al., 2010; Marshall, 2010; Warner et al., 2010; see also Section 16.3.2.3 and Box CC-EA). The adaptation literature also suggests that successful adaptation will be dependent in part on the rate at which institutions can learn to adjust to the challenges and risks posed by climate change and implement effective responses (*very high confidence*; Adger et al., 2009; Moser and Ekstrom, 2010; Stafford Smith et al., 2011).

(Dessai et al., 2009; Hulme et al., 2009; Wilby and Dessai, 2010; Verdon-Kidd et al., 2012; see also Section 2.4). Similarly, multiple authors have questioned the utility and robustness of vulnerability metrics and indices for informing adaptation decision making (Barnett et al., 2009; Klein, 2009; Hinkel, 2011; Preston et al., 2011b).

Similar tensions arise with respect to the role of traditional knowledge in adaptation. For example, cultural preferences regarding the value of traditional versus more formal scientific forms of knowledge influence what types of knowledge, and therefore adaptation options, are considered legitimate (Jones and Boyd, 2011). In the Arctic, Inuit traditional knowledge (*Inuit Qaujimajatuqangit*, IQ) encompasses all aspects of traditional Inuit culture including values, world-view, language, life skills, perceptions, and expectations (Nunavut Social Development Council, 1999; Wenzel, 2004). IQ includes, for example, weather forecasting, sea ice safety, navigation, and hunting and animal preparation skills that may have value for managing climate risk. Yet, as noted in the AR4 and more recent studies, these skills are declining among youth (*medium evidence*, *medium agreement*; Adger et al., 2007; Pearce et al., 2011). Increasing reliance on non-traditional forecasting (national weather office forecasts) and other technologies (GPS) in Arctic communities is in part responsible for increased risk taking when traveling on the land and sea ice (*medium evidence*, *medium agreement*; Aporta and Higgs, 2005; Ford et al., 2006; Pearce et al., 2011). Collectively, the recent literature suggests the extent to which knowledge acts to constrain or enable adaptation is dependent on how that knowledge is generated, shared, and used to achieve desired adaptation objectives (*very high confidence*; Patt et al., 2007; Nelson et al., 2008; Tribbia and Moser, 2008; Moser, 2010a,b).

Individual, institutional, and societal knowledge influences the capacity to develop and use technologies to achieve adaptation objectives (*very high confidence*; UNFCCC, 2006; Adger et al., 2007). The AR4 noted the role of technology in contributing to spatial and temporal heterogeneity in adaptive capacity and the potential for technology to constrain adaptation or create opportunities (Adger et al., 2007). Key considerations with respect to technology as an adaptation constraint include (1) availability; (2) access (including the capacity to finance, operate, and maintain); (3) acceptability to users and affected stakeholders; and (4) effectiveness in managing climate risk (Adger et al., 2007; Dryden-Cripton et al., 2007; van Aalst et al., 2008; see also Sections 9.4.4, 11.7, 14.2.4, 15.4.3). Although technology has implications for regional adaptive capacity (e.g., Sections 22.4.5.7, 27.3.6.2, 29.6.2), in-depth exploration of technology in the adaptation literature is often associated with specific sectors (Howden et al., 2007; Bates et al., 2008; van Koningsveld et al., 2008; EPA, 2009; Parry et al., 2009; Zhu et al., 2010). For example, Howden et al. (2007) note the importance of technology options for facilitating adaptation including applications of existing management strategies as well as introduction of innovative solutions such as bio- and nanotechnology (see also Hillie and Hlophe, 2007; Bates et al., 2008; Fleischer et al., 2011). Several studies from Africa have explored how different factors drive awareness, uptake, and use of adaptation technologies for agriculture (Nhemachena and Hassan, 2007; Hassan and Nhemachena, 2008; Deressa et al., 2009, 2011). While such literature identifies specific adaptation technology options, and in some cases the costs associated with their implementation, quantitative understanding of the extent to which improving technology will enhance adaptive capacity or reduce climate change impacts remains limited (Piao et al., 2010).

16.3.2.2. Physical Constraints

The capacity of human and natural systems to adapt to a changing climate is linked to characteristics of the physical environment including the climate itself. Recent studies have suggested that the effort required to adapt to an increase in global mean temperature of 4°C by 2100 may be significantly greater than adapting to lower magnitudes of change (*very high confidence*; Fung et al., 2011; Gemenne, 2011; New et al., 2011; Nicholls et al., 2011; Stafford Smith et al., 2011; Thornton et al., 2011; Zelazowski et al., 2011; see also Section 19.5.1). This challenge arises from the magnitude of climate change, as well as the rate (Box 16-3).

A variety of non-climatic physical factors also can constrain adaptation efforts of natural systems (*very high confidence*). For example, migration can be constrained by geographical features such as lack of sufficient altitude to migrate vertically or barriers posed by coastlines or rivers (Clark et al., 2011). Alternatively, Lafleur et al. (2010) identify soil conditions as a factor that may influence the migration of North American forests in response to climate change. Such physical barriers to migration can also arise from human activities. Feeley and Silman (2010) note that anthropogenic land use change can constrain the migration of Andean plant species to higher altitudes. Meanwhile, Titus et al. (2009) analyze state and local land use plans along the U.S. Atlantic coast and conclude that approximately 60% of coastal land below 1 meter in elevation is anticipated to be developed in the future, posing a physical barrier to inland migration of wetlands (see also Bulleri and Chapman, 2010; Jackson and McIlvenny, 2011). Collectively, such physical constraints can reduce available migration corridors and the distances over which migration is a feasible adaptive response.

Physical constraints have important implications for human adaptation as well (*medium evidence*, *high agreement*). For example, the distribution and abundance of water is a feature of the physical environment that is influenced by climate. Human consumption of freshwater increasingly is approaching the sustainable yield of surface and groundwater systems in a number of global regions (Shah, 2009; Pfister et al., 2009, 2011a,b; see also Sections 3.3.2, 3.5). Water-dependent enterprises in such regions may therefore have reduced flexibility to cope with transient or long-term reductions in water supply. This in turn influences the portfolio of adaptation actions that can be implemented effectively to manage risk to water security and, subsequently, agriculture and food security (Hanjra and Qureshi, 2010) as well as energy security (Voinov and Cardwell, 2009; Dale et al., 2011). Similarly, water quality and soil quality can constrain agricultural activities and therefore the capacity of agricultural systems to adapt to a changing climate (Delgado et al., 2011; Kato et al., 2011; Lobell et al., 2011; Olesen et al., 2011).

It is important to note, however, that these physical characteristics of the environment are often amenable to management (*very high confidence*). The AR4 presented case studies where adaptive capacity was linked to the ability of human populations or communities to access physical capital (Adger et al., 2007), such as machinery or infrastructure, to manage the environment and associated risks. Similar findings have appeared in more recent studies (Paavola, 2008; Thornton et al., 2008; Iwasaki et al., 2009; Badjeck et al., 2010; Nelson et al., 2010a,b). Human modification of the physical environment is particularly apparent in urban areas, where the location and design of buildings and infrastructure influence vulnerability to climate variability and change (Section 8.2.2.2). However, past decisions regarding the built environment and its need for continual maintenance can constrain future adaptation options and/or their costs of implementation (Section 16.3.2.10).

16.3.2.3. Biological Constraints

Since the AR4, the literature on biological (including behavioral, physiological, and genetic) tolerances of individuals, populations, and communities to climate change and extremes has continued to expand (Sections 4.4, 5.5.6, 6.2). This has resulted in a significant increase in the number of studies describing mechanisms by which biological factors can constrain the adaptation options for humans, nonhuman species, and ecological systems more broadly. In particular, biological characteristics influence the capacity of organisms to cope with increasing climate stress *in situ* through acclimation, adaptation, or behavior (Jensen et al., 2008; Somero, 2010; Tomanek, 2010; Aitken et al., 2011; Donelson et al., 2011; Gale et al., 2011; Sorte et al., 2011) as well as the rate at which organisms can migrate to occupy suitable bioclimatic regions (*very high confidence*; Morin and Thuiller, 2009; Hill et al., 2011; Feeley et al., 2012). Studies of humans also find age and geographic variation among populations with respect to perceptions of thermal comfort in indoor and outdoor space, which in turn influences the use of technologies (e.g., air conditioning, vegetation) and behavior to adjust to the thermal environment (Indraganti, 2010; Chen and Chang, 2012; Yang et al., 2012; Fuller and Bulkeley, 2013; Müller et al., 2013).

The biological capacity for migration among nonhuman species is linked to characteristics such as fecundity, phenotypic and genotypic variation, dispersal rates, and interspecific interactions (Aitken et al., 2008; Engler et al., 2009; Hellmann et al., 2012). For example, Aitken et al. (2008)

argue that migration rates of tree species necessary to track a changing climate are higher than what has been observed since the last glaciation. However, Kremer et al. (2012) note that long-distance gene flow of tree species can span distances in one generation that are greater than habitat shifts predicted under climate change. Additional research is needed to clarify the capacity of species and communities to migrate in response to a changing climate.

The degradation of environmental quality is another source of constraints (*very high confidence*; Côté and Darling, 2010), with multiple studies including natural capital as a foundation for sustainable livelihoods (Paavola, 2008; Thornton et al., 2008; Iwasaki et al., 2009; Badjeck et al., 2010; Nelson et al., 2010a,b). Non-climatic stresses to ecological systems can reduce their resilience to climate change as evidenced by studies on coral reefs and marine ecosystems, tropical forests, and coastal wetlands (*very high confidence*; Diaz and Rosenberg, 2008; Kapos and Miles, 2008; Malhi et al., 2009a,b; Afreen et al., 2011; see also Section 4.2.4 and Box CC-CR). For example, several studies have noted interactions between anthropogenic land use change and species migration rates on the risk of extirpation (Feeley et al., 2010; Yates et al., 2010; Cabral et al., 2013; Svenning and Sandel, 2013).

Ecological degradation also reduces the availability of ecosystem goods and services for human populations (*very high confidence*; Nkem et al., 2010; Tobey et al., 2010; see also Sections 4.4.3, 6.4.1). For example, degradation of coastal wetlands and coral reef systems may reduce their capacity to buffer coastal systems from the effects of tropical cyclones (Das and Vincent, 2009; Tobey et al., 2010; Gedan et al., 2011; Keryn et al., 2011; Box CC-EA). Similarly, soil degradation and desertification can reduce crop yields and the resilience of agricultural and pastoral livelihoods to climate stress (Iglesias et al., 2011; Lal, 2011).

Ecosystem constraints can also arise from non-native species, including pests and disease, that compete with endemic species (Hellman et al., 2008; Dukes et al., 2009; Moser et al., 2011; Ziska et al., 2011; Pautasso et al., 2012; Svobodová et al., 2013; see also Section 4.2.4.6). Climate change could reduce the effectiveness of current control mechanisms for invasive species (*very low confidence*; Hellmann et al., 2008). However, studies also indicate that uncertainty associated with predictions of future pests, disease, and invasive species remains high (Dukes et al., 2009).

16.3.2.4. Economic Constraints

The AR4 concluded that adaptive capacity is influenced by the entitlements of actors to economic resources and by larger macro-level driving forces such as economic development and trends in globalization (Adger et al., 2007). More recent literature continues to identify economic constraints associated with adaptation. However, such constraints often involve the financing of discrete adaptation options (e.g., Matasci et al., 2013; Islam et al., 2014). This chapter draws a distinction between such financial constraints (Section 16.3.2.5) and economic constraints, which are associated with broader macroeconomic considerations.

Long-term trends in economic development as well as short-term dynamics in economic systems can have a significant influence on the capacity of actors to adapt to climate change (*very high confidence*; Section 16.3.1.1). Multiple authors, for example, discuss the concept of "double exposure" where actors are subjected to stresses associated with climate change as well as those associated with economic disruptions such as the recent global financial crisis or other stresses (Leichenko et al., 2010; Silva et al., 2010; Leichenko, 2012; Jeffers, 2013; McKune and Silva, 2013). Similarly, Kiem and Austin (2013) argue that prevailing economic conditions have an important influence on the capacity of Australian farmers to cope with drought.

The implications of economic constraints vary among different sectors that have differential vulnerability to climate change. Economies that are disproportionately composed of climate-sensitive sectors such as agriculture, forestry, and fisheries may be particularly vulnerable to the effects of climate change and may encounter greater constraints on their capacity to adapt (*very high confidence*). Such economies occur disproportionately in the developing world (Thornton et al., 2008; Allison et al., 2009; Feng et al., 2010; Füssel, 2010), although multiple studies have explored climate-sensitive regional economies in developed nations as well (Edwards et al., 2009; Leichenko et al., 2010; Aaheim et al., 2012; Kiem and Austin, 2013). Poverty and development deficits that are linked to economic conditions also exist in urban areas (Sections 8.1.3, 8.3.2.1).

While economic development and diversification are generally seen as factors that can ameliorate resource deficits (Sections 20.2.1.2, 20.3.2), certain economic enterprises can constrain adaptation. For example, the AR4 noted that activities such as shrimp farming and conversion of coastal mangroves, though profitable in an economic sense, can exacerbate vulnerability to sea level rise (Agrawala et al., 2005; Adger et al., 2007). More recent studies have demonstrated that economic development and urbanization of hazardous landscapes may increase human exposure to extreme weather events and climate change, resulting in greater economic losses and risks to public health and safety (Baldassare et al., 2010; IPCC, 2012; Preston, 2013). Economic development also can put pressure on natural resources and ecosystems that can constrain their capacity to adapt (Titus et al., 2009; Sydneysmith et al., 2010; see also Sections 16.3.2.3, 20.3.2). The extent to which economic development creates opportunities or constrains adaptation is dependent on the development pathway (Section 20.6). Low resource-intensive economic growth can enhance adaptive capacity while minimizing externalities of development that can increase vulnerability of human and natural systems (Section 20.6).

16.3.2.5. Financial Constraints

In addition to broader macroeconomic constraints on adaptation (Section 16.3.2.4), the implementation of specific adaptation strategies and options can be constrained by access to financial capital (*very high confidence*). Financial capital can manifest in a variety of forms including credit, insurance, and tax revenues, as well as earnings of individual households or private entities. The AR4 concluded that the global costs of adaptation could be quite substantial over the next several decades (Adger et al., 2007). More recent studies suggest costs on the order of US$75 to US$100 billion per year by 2050 (Section 17.4; Table 17-2). In the context of the UNFCCC, mechanisms have been established to help meet these costs. The Least Developed Country Fund was established to assist developing nations in generating National Adaptation Plans of Action (Sections 14.4.4, 15.2.3). The Adaptation Fund was established within the context of the UNFCCC to finance adaptation in developing nations through the sale of certified emissions reductions (CERs) credits under the Clean Development Mechanism (Sections 14.3.2, 15.2.2.1). Nevertheless, declines in CER credit prices since early 2011 have reduced the flow of revenue to the Adaptation Fund (Adaptation Fund Board, 2013), and the demand for adaptation finance in general is larger than the current availability of resources represented through these funds (Bouwer and Aerts, 2006; Flåm and Skjærseth, 2009; Hof et al., 2009). Furthermore, developing a framework for the equitable and effective allocation of adaptation funds to developing nations is a non-trivial challenge (Smith et al., 2009a; Barr et al., 2010).

Overseas development assistance (ODA) represents another mechanism for channeling financial capital into adaptation programs and projects. However, multiple authors have identified potential constraints associated with the use of ODA for financing adaptation, including concerns among donors for the effectiveness of ODA (Kalirajan et al., 2011), lack of incentives among donors to allocate ODA to adaptation (Buob and Stephan, 2013), and potential for allocation of ODA to adaptation to reduce the availability of funds for achieving development goals (Ayers and Huq, 2009).

The potential for finance to constrain adaptation also emerges from a broad range of recent case studies exploring adaptive capacity in different sector and regional contexts, although finance is often identified as just one of a broad range of resource constraints (Paavola, 2008; Jantarasami et al., 2010; Moser and Ekstrom, 2010; Osbahr et al., 2010; Biesbroek et al., 2013a). Investigations of farming communities in Africa have identified finance as a key determinant of vulnerability and adaptive capacity of farmers to climate variability and change (Nhemachena and Hassan, 2007; Hassan and Nhemachena, 2008; Deressa et al., 2009, 2011). Islam et al. (2014) cite access to credit as a key constraint on adaptation among fishing communities in Bangladesh, and financial constraints have also been documented in municipal governments in South Africa (Pasquini et al., 2013). Huntington et al. (2012) question whether relocating the 184 Alaskan Native villages threatened by coastal erosion and inundation is politically feasible given the high costs, estimated at up to US$1 million per person or US$100 million per village on average.

Institutions in developed nations face constraints in funding adaptation options despite their comparatively high adaptive capacity. For example, Jantarasami et al. (2010) report that staff from U.S. federal land management agencies identified resource constraints as a key barrier to adaptation. Similarly, surveys and interviews with state and local government representatives in Australia indicate that the costs of investigating and responding to climate change are perceived to be significant constraints on adaptation at these levels of governance (Smith et al., 2008b; Gardner et al., 2010; Measham et al., 2011). However, Burch (2010) argues that financial constraints on adaptation reported by local governments in Canada are secondary to other institutional practices and cultures (Section 16.3.2.8).

Insurance represents a cross-cutting financial instrument that is relevant to a range of public and private institutions in both developing and developed nations. While insurance can represent an opportunity to influence decision making regarding climate risk management (Næss et al., 2005; Herweijer et al., 2009; see also Section 10.7), reduced accessibility and/or increased costs of insurance can constrain the utility of insurance as an adaptation option (Herwijer et al., 2009; Islam et al., 2014; see also Section 10.7).

16.3.2.6. Human Resource Constraints

The effectiveness of societal efforts to adapt to climate change is dependent on humans who are the primary agents of change (*very high confidence*). Human resources provide the foundation for intelligence gathering, the uptake and use of technology, as well as leadership regarding the prioritization of adaptation policies and measures and their implementation. Although the AR4 and subsequent adaptation literature identify human resources as one of the factors influencing adaptive capacity (Adger et al., 2007), there has been little attention given specifically to human resources as a constraint on adaptation by adaptation researchers. Rather the literature mentions human resources in two principal contexts. First, it highlights the linkages between the development of human resources and adaptive capacity more broadly. For example, Ebi and Semenza (2008) treat human resources as part of the portfolio of resources that can be harnessed to facilitate adaptation in the public health arena. Similarly, Nelson et al. (2010a,b) use human capital as one indicator of the capacity of rural communities to cope with climate impacts. In addition, a number of recent studies call attention to the role of leadership in enabling or constraining organizational adaptation (Gupta et al., 2010; Tompkins et al., 2010; van der Berg et al., 2010; Termeer et al., 2012). Murphy et al. (2009) discuss the emergence of institutions to build human resources in the climate change arena, including expanded higher education opportunities to build climate expertise as well as professional societies. Second, the literature highlights the finite nature of human resources as a need to prioritize adaptation efforts including the extent of engagement in participatory processes (van Aalst et al., 2008) as well as the selection of adaptation actions for implementation (Millar et al., 2007).

16.3.2.7. Social and Cultural Constraints

Adaptation can be constrained by social and cultural factors that are linked to societal values, world views, and cultural norms and behaviors (*very high confidence*; O'Brien, 2009; Moser and Ekstrom, 2010; O'Brien and Wolf, 2010; Hartzell-Nichols, 2011). These social and cultural factors can influence perceptions of risk, what adaptation options are considered useful and by whom, as well as the distribution of vulnerability and adaptive capacity among different elements of society (Grothmann and Patt, 2005; Weber, 2006; Patt and Schröter, 2008; Adger et al., 2009; Kuruppu, 2009; O'Brien, 2009; Nielsen and Reenberg, 2010; Wolf and Moser, 2011; Wolf et al., 2013). Although the AR4 noted that social and cultural constraints on adaptation have not been well researched, more recent literature has significantly expanded their understanding. As a case in point, the erosion of traditional knowledge among the Arctic Inuit is the consequence of a long-term process of changing livelihoods, technology, and sources of knowledge (Pearce et al., 2011; see also Section 16.3.2.1). Studies from the USA indicate that increasing demand

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for amenity lifestyles is resulting in the settlement of individuals in locations where there is little experience or oral history regarding natural hazards—a phenomenon that subsequently influences risk perception and engagement in risk management (Heyd and Brooks, 2009; Gordon et al., 2013).

Different actors within and among societies experience different constraints, which result in differential adaptive capacities and preferences for adaptation options (Wolf et al., 2013). As discussed in the AR4, for example, gender can be a factor that constrains adaptation. Recent studies from Nepal and India report that adaptation decisions among women, in particular, can be constrained by cultural and institutional pressures that favor male land ownership (Jones and Boyd, 2011) and constrain access to hazard information (Ahmed and Fajber, 2009), respectively. Studies of evacuation during Hurricane Katrina suggest that females were more likely to evacuate New Orleans than males (Brunsma et al., 2010), as were individuals without sufficient resources and access to transportation (Cutter and Emrich, 2006). Studies from both the USA and UK find that the elderly do not necessarily perceive themselves as vulnerable to extreme heat events (Sheridan, 2007; Wolf et al., 2009), which may create disincentives to react to such events (Chapter 11).

Barriers to taking action have also been attributed to sense of place, which shapes individual identity (Adger et al., 2011, 2012; Fresque-Baxter and Armitage, 2012). Foresight (2011) notes that processes that constrain migration could be maladaptive, resulting in the abandonment of livelihoods or geographic locations. For example, Park et al. (2012) find that sense of place attachment among some wine grape growers in Australia precludes consideration for migration to other growing areas in response to a changing climate.

Case studies from multiple developing countries report that some actors view natural phenomena as being controlled by God, supernatural forces, or ancestral spirits that are not amenable to human management (Sehring, 2007; Schipper, 2008; Byg and Salick, 2009; Mustelin et al., 2010; Kuruppu and Liverman, 2011; Artur and Hilhorst, 2012). Such perspectives are not confined to the developing world. Surveys conducted after Hurricane Katrina also indicated that religious beliefs were a factor influencing the decision to remain rather than evacuate (Brunsma et al., 2010). Yet, religion was also identified as a factor that enabled affected individuals to cope with the stress of the event.

16.3.2.8. Governance and Institutional Constraints

Research conducted since the AR4 has expanded understanding of adaptation constraints associated with governance, institutional arrangements, and legal and regulatory issues. Adaptation to climate change will necessitate the mobilization of resources, decision making, and the implementation of specific policies by societal institutions (Huang et al., 2011). Yet, these processes may be most effective when they are aligned to the given context and group of actors (Berkhout, 2012; Garschagen, 2013). The adaptation literature provides extensive evidence that institutional capacity is a key factor that can potentially constrain the adaptation process (*very high confidence*; Berkhout, 2012). Lesnikowski et al. (2013), for example, find that planned adaptation by the public health sector among different nations is significantly associated with national GDP. Similarly, it has been argued that U.S. institutions across different levels of governance lack the mandate, information, and/or professional capacity to select and implement adaptation options (National Research Council, 2009). Institutional capacity may be linked to the level of priority assigned to adaptation (Keskitalo et al., 2010; Westerhoff et al., 2010; Maibach et al., 2011; Measham et al., 2011; Sowers et al., 2011). For example, Ebi et al. (2009) argue that U.S. public health agencies allocate less than US$3 million per year to address climate change, yet a budget greater than US$200 million is needed to adequately address the problem. Keskitalo (2010) and Lesnikowski et al. (2013) find that adaptation efforts are associated with the extent to which institutions prioritize environmental management more broadly. Corruption within institutions may also undermine adaptation efforts, as evidenced by empirical studies among multiple nations (Lesnikowski et al., 2013), as well as case studies within nations (Schilling et al., 2012).

A key role that institutions play in facilitating adaptation is through legal and regulatory responsibilities and authorities (*very high confidence*). Multiple studies have documented the adaptation constraints affecting institutions in Australia engaged in the development of local and regional planning policy (Pini et al., 2007; Measham et al., 2011; Matthews, 2013). Similar capacity constraints have been observed within institutions governing Canada's Inuit population (Ford et al., 2010). Li and Huntsinger (2011) observe how increasing land privatization and the institutionalization of rigid land tenure in the Inner Mongolia region of China have reduced the resilience of pastoralists to cope with drought, although the lack of secure land tenure has been found to constrain adaptation in other contexts (Almansi, 2009; Ebi et al., 2011; Hisali et al., 2011; Larson, 2011; see also Sections 8.4.2.2, 9.3.5.1.3). In addition to such capacity issues, multiple studies from both developed and developing nations suggest that the current structure of institutions and regulatory policies may be poorly aligned to achieve adaptation objectives (Craig, 2010; Spies, 2010; Stillwell et al., 2010; Stuart-Hill and Schulze, 2011; Eisenack and Stecker; 2012; Huntjens et al., 2012; Herrfahrdt-Pähle, 2013). Changing legal principles to accommodate more forward-looking adaptation responses as opposed to basing them on historical precedent and practice may be a difficult process (Craig, 2010; McDonald, 2011).

Adaptation can also be constrained owing to the complexities of governance networks that are often composed of multiple actors and institutions such as government agencies, market actors, NGOs, as well as informal community organizations and social networks (*very high confidence*; Rosenau, 2005; Adger et al., 2009; Juhola and Westerhoff, 2011; Carlsson-Kanyama et al., 2013; Sosa-Rodriguez, 2013). Coordination among these different actors is important for facilitating adaptation decision making and implementation (Young, 2006; van Nieuwaal et al., 2009; Grothmann, 2011). Yet, different actors may have different objectives, jurisdictional authority, as well as levels of power or resources. Adaptation efforts may recognize these constraints, but do not necessarily articulate institutional arrangements that facilitate their coordination and reconciliation to achieve common adaptation objectives (Zinn, 2007; Preston, 2009; Birkmann et al., 2010; see also Section 15.5.1). This may arise, in part, from the dominant focus of the adaptation discourse on formal, public institutions of governance

(Eisenack et al., 2012), although work examining the role of private institutions has emerged recently (Tompkins et al., 2010; CDP, 2012; Mees et al., 2012; Taylor et al., 2012; Tompkins and Eakin, 2012; EBI, 2013; see also Section 14.2.4).

Actors and institutions associated with different scales may have different perceptions of the need for adaptation as well as the factors that constrain or enable adaptation (*very high confidence*; Biesbroek et al., 2011). In this context, scale refers to analytical dimensions used to study adaptation (including spatial, temporal, institutional, or jurisdictional), and each scale can be comprised of multiple levels (e.g., local to global in the context of spatial scales or household to central government in the context of jurisdictions of governance) (Cash et al., 2006; Adger et al., 2009). A large number of studies have emerged since the AR4 that focus on how local adaptation efforts are constrained by higher levels of governance, such as state or federal governments or private companies (Urwin and Jordan, 2008; Huntjens et al., 2010; Abel et al., 2011; Measham et al., 2011; Pittock, 2011; Westerhoff et al., 2011; Amaru and Chhetri, 2013; Carlsson-Kanyama et al., 2013; Mukheibir et al., 2013; Sosa-Rodriguez, 2013). This has led some to question whether it is appropriate to consider adaptation as an exclusively local process (Burton et al., 2008; Preston et al., 2013b). For example, a study of adaptation policy initiatives in EU member countries concluded that central governments can play a significant role in supporting local adaptation policies. However, in cases where there is weak top-down leadership on adaptation, it may be useful to have less centralized mechanisms for supporting local adaptation efforts (Keskitalo, 2010). In addition, EU funding has enabled local adaptation even in the absence of funding from the relevant EU member state (Keskitalo, 2010), suggesting opportunities exist for transnational governance to overcome adaptation constraints.

Other authors have also noted that informal social institutions may help to extend the reach of formal government actors (Wolf et al., 2010; Juhola and Westerhoff, 2011) or drive adaptation processes when formal actors are unable to do so (Measham and Preston, 2012). Adaptation planning and implementation thus creates new governance challenges, and new institutions and bridging organizations may be needed to facilitate integration of complex planning processes across scales (*medium evidence*, *high agreement*; Preston, 2009; National Research Council, 2010; UKCIP, 2011).

16.3.2.9. Constraints and Competing Values

A number of the aforementioned types of adaptation constraints arise from a common cause—the differential values of societal actors and the trade-offs associated with prioritizing and implementing adaptation options (*very high confidence*; Haddad, 2005; UNEP, 2011; see also Section 2.3.3 and Table 16-2). At the international level, for example, agreements such as the Bali Action Plan (UNFCCC, 2007a) and Cancun Adaptation Framework (UNFCCC, 2011) indicate that deliberation over how the adaptation needs of least developed countries will be financed has become central to the UNFCCC policy agenda (see also UNFCCC, 2007b; Ayers and Huq, 2009; Dellink et al., 2009; Flåm and Skjærseth, 2009; Denton, 2010; Patt et al., 2010a). Yet the extent to which the developed world bears responsibility for compensating the developing world for climate impacts has been a contentious issue (Hartzell-Nichols, 2011). Rayner and Jordan (2010) and Brouwer et al. (2013) report concern among EU water policy makers that adaptation may undermine efforts to maintain water quality. For example, technological solutions to enhance water supply in a changing climate may occur at the expense of water quality. Alternatively, placing adaptation on the policy agenda may create the perception that climate change will eventually necessitate the acceptance of reduced water quality. At the local level, Measham et al. (2011) report that some local governments in Australia find it difficult to pursue adaptation efforts owing to perceived conflicts between potential adaptation options and the values and preferences of individuals and stakeholder groups within the community.

Such potential differences among stakeholders regarding adaptation options may result in some actions being simultaneously perceived as adaptive and maladaptive (*limited evidence*, *medium agreement*; Bardsley and Hugo, 2010). Maladaptation arises from the implementation of adaptation options that increase the vulnerability of individuals, institutions, sectors, or regions (Barnett and O'Neill, 2010). Individuals or institutions may have specific management objectives or values that they seek to achieve or maintain through adaptation (Section 16.2, Table 16-2). For every objective, however, there may be multiple adaptation options, each of which is associated with a particular set of costs, benefits, and externalities. For example, biotechnology may contribute to the development of drought- and pest-resistant cultivars that can maintain or enhance yields despite more challenging climate conditions. Yet, ecological and public health concerns over the use of biotechnology and genetically modified crops, in particular, can constrain the use of such technologies (Table 16-2). Agricultural producers may view biotechnology as an adaptive response, while some consumers may view it as a maladaptation that increases risks to ecosystems and food security. Similar types of trade-offs can be identified across different sectors (Table 16-2), and thus a challenge in adaptation planning and implementation is determining who decides what options are adaptive or maladaptive and successful or unsuccessful. The potential for maladaptation or for some adaptation options to undermine sustainability (Eriksen et al., 2011) suggests that actors may choose to regulate adaptation and deliberately constrain possible options to avoid adverse externalities (*very low confidence*).

Recognizing the potential for values conflicts to constrain adaptation, researchers and practitioners have advocated for so-called "no regrets" or "low regrets" adaptation strategies that create net benefits under the current climate as well as a range of future potential climates (Hallegatte, 2009; Heltberg et al., 2009). Such strategies can focus adaptation efforts on options where there are fewer perceived trade-offs (Preston et al., 2013b). However, identifying options that are perceived as having no regrets across all potential stakeholders may be quite difficult (Merz et al., 2010; Preston et al., 2013b), and it has been suggested such strategies may reduce the perceived need for more substantive adaptations necessary to protect highly vulnerable systems or avoid irreversible consequences (Preston et al., 2013b). Reconciling such trade-offs may necessitate deliberation among decision makers and other stakeholders regarding adaptation objectives and the manner in which competing or conflicting values can be reconciled to achieve outcomes (de Bruin et al., 2009b; McNamara and Gibson, 2009; McNamara et al., 2011; UNEP, 2011).

Table 16-2 | Examples of potential trade-offs associated with an illustrative set of adaptation options that could be implemented by actors to achieve specific management objectives.

Sector	Actor's adaptation objective	Adaptation option	Real or perceived trade-off	References
Agriculture	Enhance drought and pest resistance; enhance yields	Biotechnology and genetically modified crops	Perceived risk to public health and safety; ecological risks associated with introduction of new genetic variants to natural environments	Howden et al. (2007); Nisbet and Scheufele (2009); Fedoroff et al. (2010)
	Provide financial safety net for farmers to ensure continuation of farming enterprises	Subsidized drought assistance; crop insurance	Creates moral hazard and distributional inequalities if not appropriately administered	Productivity Commission (2009); Pray et al. (2011); Trærup (2011); O'Hara (2012); Vermeulen et al. (2012)
	Maintain or enhance crop yields; suppress opportunistic agricultural pests and invasive species	Increased use of chemical fertilizer and pesticides	Increased discharge of nutrients and chemical pollution to the environment; adverse impacts of pesticide use on non-target species; increased emissions of greenhouse gases; increased human exposure to pollutants	Gregory et al. (2005); Howden et al. (2007); Boxall et al. (2009)
Biodiversity	Enhance capacity for natural adaptation and migration to changing climatic conditions	Migration corridors; expansion of conservation areas	Unknown efficacy; concerns over property rights regarding land acquisition; governance challenges	Hodgson et al. (2009); West et al. (2009); Krosby et al. (2010); Levin and Petersen (2011)
	Enhance regulatory protections for species potentially at risk due to climate and non-climatic changes	Protection of critical habitat for vulnerable species	Addresses secondary rather than primary pressures on species; concerns over property rights; regulatory barriers to regional economic development	Clark et al. (2008); Ragen et al. (2008); Bernanzzani et al. (2012)
	Facilitate conservation of valued species by shifting populations to alternative areas as the climate changes	Assisted migration	Difficult to predict ultimate success of assisted migration; possible adverse impacts on indigenous flora and fauna from introduction of species into new ecological regions	Lovejoy (2005, 2006); McLachlan et al. (2007); Dunlop and Brown (2008)
Coasts	Provide near-term protection to financial assets from inundation and/or erosion	Sea walls	High direct and opportunity costs; equity concerns; ecological impacts to coastal wetlands	Nicholls (2007); Hayward (2008); Hallegatte (2009); Zhu et al. (2010)
	Allow natural coastal and ecological processes to proceed; reduce long-term risk to property and assets	Managed retreat	Undermines private property rights; significant governance challenges associated with implementation	Rupp-Armstrong and Nicholls (2007); Hayward (2008); Abel et al. (2011); Titus (2011)
	Preserve public health and safety; minimize property damage and risk of stranded assets	Migration out of low-lying areas	Loss of sense of place and cultural identify; erosion of kinship and familial ties; impacts to receiving communities	Hess et al. (2008); Heltberg et al. (2009); McNamara and Gibson (2009); Adger et al. (2011)
Water resources management	Increase water resource reliability and drought resilience	Desalination	Ecological risk of saline discharge; high energy demand and associated carbon emissions; creates disincentives for conservation	Adger and Barnett (2009); Barnett and O'Neill (2010); Becker et al. (2010, 2012); Rygaard et al. (2011); Tal et al. (2011)
	Maximize efficiency of water management and use; increase flexibility	Water trading	Undermines public good/social aspects of water	Alston and Mason (2008); Bourgeon et al. (2008); Donohew (2008); Mooney and Tan (2012); Tan et al. (2012)
	Enhance efficiency of available water resources	Water recycling/reuse	Perceived risk to public health and safety	Hartley (2006); Dolcinar et al. (2011)

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16.3.2.10. Consideration of Cross-Scale Dynamics

The AR4 noted that adaptation processes can be constrained by interactions and dynamics within or among different scales (Adger et al., 2007). Recent literature since the AR4 has expanded understanding of vulnerability and adaptive capacity as a cross-scale and multilevel process. The vulnerabilities of different communities, regions, and sectors are linked through processes and feedbacks that span multiple scales and levels (*medium evidence*, *high agreement*). Adger et al. (2008) and Eakin et al. (2009) refer to this phenomenon as "nested and teleconnected vulnerability."

A number of recent studies focused on agriculture and global commodities provide evidence of this phenomenon. Adger et al. (2008) and Eakin et al. (2009) illustrate such teleconnected vulnerability with case studies of coffee production. Although coffee is a global commodity, the majority of production occurs in developing nations among small-scale farmers. As such, household vulnerability and adaptive capacity among coffee farmers is linked to global markets and coffee prices as well as local environmental conditions and policies. Such interactions were also apparent in 2006–2008 and again in 2010–2011 when global food commodity prices increased sharply in part due to the impacts of extreme weather events on food-producing regions (FAO, 2011). The resulting increase in food prices benefited producers that were unaffected by the drought and were able to capitalize on higher prices, but higher prices adversely affected consumer welfare and food security (Abbott and de Battisti, 2009; Woden and Zaman, 2009; FAO, 2011).

Similar constraints on adaptation arise in the context of transboundary water resources where river management is influenced by processes occurring at different jurisdictional levels (i.e., local, regional, national, and international water policies and management practice) as well as different spatial levels (e.g., linkages between global climate change and climate trends at more regional or local levels) (Iglesias et al., 2007;

Goulden et al., 2009; Huntjens et al., 2010; Krysanova et al., 2010; Timmerman et al., 2011; Wilby and Keenan, 2012; Milman et al., 2013).

Constraints on adaptation are also associated with temporal scaling. A key factor constraining future adaptation options and costs is path dependence (*very high confidence*), which Preston (2013, p. 719) defines as "the dependence of future societal decision processes and/or socio-ecological outcomes on those that have occurred in the past." Libecap (2010) suggests that water infrastructure developed in the U.S. West in the late-19th and early 20th centuries has constrained management choice regarding water allocation in the present. Chhetri et al. (2010) suggest similar constraints may exist for the U.S. agricultural industry in the future owing to constraints on farmers' capacity to alter management practices and technology in response to a changing climate. Major development of water management and allocation systems in watersheds of Australia and the U.S. Southeast over the latter half of the 20th century occurred during periods of favorable rainfall relative to long-term instrumental and paleo records (Jones and Pittock, 2002; Jones, 2010; Chiew et al., 2011; Pederson et al., 2012), and thus those systems were adapted to conditions that were not representative of the long-term risk of extensive drought (Jones and Pittock, 2002; Jones, 2010; Connell and Grafton, 2011; Pederson et al., 2012).

Adjusting large-scale, complex systems and institutional behavior established by past decision making can be costly. The Australian government, for example, has engaged in a water management reform process since the 1980s (Connell and Grafton, 2011), and in recent years has committed more than AUS$12.9 billion for a number of initiatives to address historical resource over-allocation and support sustainable water management practices in the Murray-Darling Basin (Commonwealth of Australia, 2010).

To avoid adverse outcomes associated with path dependence, literature on flexible adaptation pathways emphasizes the implementation of reversible and flexible options that allow for ongoing adjustment (Stafford Smith et al., 2011; Haasnoot et al., 2013). In addition, the literature on "real options" suggests that, under certain circumstances, there may be value in such flexible adaptation strategies or in delaying investments in certain adaptation options until new information or management options are available (Hertzler, 2007; Dobes, 2008; Jeuland and Whittington, 2013).

16.4. Limits to Adaptation

The various constraints discussed previously (Section 16.3.2) can, if sufficiently severe, pose limits to the ability of actors to adapt to climate change (*medium evidence*, *high agreement*; Meze-Hausken, 2008; Adger et al., 2009; O'Brien, 2009; Moser and Ekstrom, 2010; Dow et al., 2013a,b). A limit is reached when adaptation efforts are unable to provide an acceptable level of security from risks to the existing objectives and values and prevent the loss of the key attributes, components, or services of ecosystems (Box 16-1). For example, one of the key messages from the WGII AR5 chapter on Africa (Chapter 22) is, "Progress is being achieved on managing risks to food production from current climate variability but these will likely not be sufficient to address long-term risks from climate change (*high confidence*)."

There are a variety of circumstances and terminology in the literature that imply adaptation limits including "thresholds" (Meze-Hausken, 2008; Briske et al., 2010; Washington-Allen et al., 2010); "regime shifts" (Washington-Allen et al., 2010); "tipping points" (Lenton et al., 2008; Kriegler et al., 2009); "dangerous climate change" (Mastrandrea and Schneider, 2004; Ford, 2009a); "reasons for concern" (Smith et al., 2009a); "planetary boundaries" (Rockström et al., 2009); or "key vulnerabilities" (Schneider et al., 2007; Hare et al., 2011; Johannessen and Miles, 2011; see also Section 19.6). In addition, terms such as barriers, constraints, and limits are sometimes used interchangeably. Owing to this diversity in language, this discussion builds on recent efforts to develop a common lexicon to facilitate research and practice (Hulme et al., 2007; Adger et al., 2009; Dow et al., 2013a,b; see also Section 16.2 and Box 16-1).

16.4.1. Hard and Soft Limits

Although limits to adaptation are at times described in the literature as fixed thresholds (Adger et al., 2009), recent studies have emphasized the need to consider the perspective of actors in defining adaptation limits (Adger et al., 2009; Dow et al., 2013 a,b; see also Sections 16.1-2) as well as the dynamic nature of both biophysical and socioeconomic processes that influence adaptation decision making and implementation (Park et al., 2012; Preston et al., 2013a; Islam et al., 2014). Informed by the distinctions drawn in the work of Meze-Hausken (2008), Adger et al. (2009), and Moser and Ekstrom (2010), one can distinguish between "hard" limits, those that will not change, and "soft" limits, which could change over time. For human actors, whether a limit is hard or soft is usefully evaluated at a given point in time by asking whether an adaptation response to manage an intolerable risk could emerge in the future. For example, projected climate change impacts in Europe indicate that increasing irrigation needs will be constrained by reduced runoff, demand from other sectors, and economic costs. As a consequence, by the 2050s, farmers will be limited by their inability to use irrigation to prevent damage from heat waves to crops (Sections 23.4.1, 23.4.3). For natural systems, whether a limit is hard or soft is defined by the rate and capacity of species and ecosystem responses relative to environmental changes (Shaw and Etterson, 2012).

Discussions of hard limits in the literature are often associated with thresholds in physical systems that, if exceeded, would lead to irreversible changes or the loss of critical structure or function (Lenton et al., 2008; Adger et al., 2009; IPCC, 2012). Such limits arise from the magnitude and/or rate of climate change (Box 16-3). For example, a number of physical thresholds in the Earth system have been proposed as posing potential limits to adaptation, particularly large-scale events such as irreversible melting of the Greenland or Antarctic ice sheets (Schneider and Lane, 2006a; Sheehan et al., 2008; Travis, 2010). Such physical thresholds, however, though relevant to understanding adaptation limits, are not necessarily limits in themselves as they neglect consideration for the adaptive capacity of natural and human systems (Adger et al., 2009; Leary et al., 2009; Dow et al., 2013a,b; Klein and Juhola, 2013; Preston et al., 2013a).

For species and ecosystems, hard limits to adaptation are often associated with exceedance of the physiological capacity of individual organisms

Box 16-4 | Historical Perspectives on Limits to Adaptation

Does human history provide insights into societal resilience and vulnerability under conditions of environmental change? Archeological and environmental reconstruction provides useful perspectives on the role of environmental change in cases of significant societal change, sometimes termed "collapse" (Diamond, 2005). These may help to illuminate how adaptation limits were either exceeded, or where collapse was avoided to a greater or lesser degree. Great care is necessary to avoid oversimplifying cause and effect, or overemphasizing the role of environmental change, in triggering significant societal change, and the societal response itself. Coincidence does not demonstrate causality, such as in the instance of matching climatic events with social crises through the use of simple statistical tests (Zhang et al., 2011), or through derivative compilations of historical data (deMenocal, 2001; Thompson et al., 2002; Drysdale et al., 2006; Butzer, 2012). Application of social theories may not explain specific cases of human behavior and community decision making, especially because of the singular importance of the roles of leaders, elites, and ideology (Hunt, 2007; McAnany and Yoffee, 2010; Butzer, 2012; Butzer and Endfield, 2012).

There are now roughly a dozen case studies of historical societies under stress, from different time ranges and several parts of the world, that are sufficiently detailed (based on field, archival, or other primary sources) for relevant analysis (Butzer and Endfield, 2012). These include Medieval Greenland and Iceland (Dugmore et al., 2012; Streeter et al., 2012), Ancient Egypt (Butzer, 2012), Colonial Cyprus (Harris, 2012), the prehistoric Levant (Rosen and Rivera-Collazo, 2012), Islamic Mesopotamia and Ethiopia (Butzer, 2012), the Classic Maya (Dunning et al., 2012; Luzzadder-Beach et al., 2012), and Colonial Mexico (Endfield, 2012). Seven such civilizations underwent drastic transformation in the wake of multiple inputs, triggers, and feedbacks, with unpredictable outcomes. These can be seen to have exceeded adaptation limits. Five other examples showed successful adaptation through the interplay of environmental, political, and socio-cultural resilience, which responded to multiple stressors (e.g., insecurity, environmental or economic crises, epidemics, famine). In these cases, climatic perturbations are identified as only one of many "triggers" of potential crisis, with preconditions necessary for such triggers to stimulate transformational change. These preconditions include human-induced environmental decline mainly through overexploitation.

Avoidance of limits to adaptation requires buffering feedbacks that encompass social and environmental resilience. Exceedance of limits occurred through cascading feedbacks that were characterized by social polarization and conflict that ultimately result in societal disruption. Political simplification undermined traditional structures of authority to favor militarism, while breakdown was accompanied or followed by demographic decline. Although climatic perturbations and environmental degradation did contribute to triggering many cases of breakdown, the most prominent driver at an early stage was institutional failure, which refers to the inability of societal institutions to address collective-action problems (Acheson, 2006). In these cases, collapse was neither abrupt nor inevitable, often playing out over centuries. Lessons from the implementation of adaptation responses over historical time periods in Mexico City suggest that some responses may create new and even more significant risks (Sosa-Rodriguez, 2010).

Recent work on resilience and adaptation synthesizes lessons from extreme event impacts and responses in Australia (Kiem et al., 2010). This further emphasizes an institutional basis for resilience, finding that government intervention through the provision of frameworks to enable adaptation is beneficial. Furthermore, it was found that a strong government role may be necessary to absorb a portion of the costs associated with natural disasters. On the other hand, community awareness and recognition of novel conditions were also found to be critical elements of effective responses. It would be useful to consider how lessons learned from historical experience may relate to the perceived multiple environmental changes characterized by the "Anthropocene" era (Crutzen, 2002).

or communities to adapt to changes in the climate (i.e., temperature, rainfall, and/or disturbance regimes; Peck et al., 2009), or to climate-induced changes in the abiotic environment (e.g., ocean circulation and stratification; Harley et al., 2006; Doney et al., 2012; see also Sections 16.3.2.2-3). Such systems tend to be those that persist at the upper limit of their climate tolerances (Sheehan et al., 2008; Benito et al., 2011; Dirnböck et al., 2011); those for which sustainability is closely tied to vulnerable physical systems (Johannessen and Miles, 2011); or those that are under significant pressure from non-climatic forces (Jenkins et al., 2011). For example, many species, including humans (Section 11.8.1) and key food crops (e.g., wheat, maize, and rice; Sections 7.3.2, 11.8.2), are known to have thermal limits to survival. Similarly, increased ocean acidity is expected to reduce the ability of some marine organisms such as corals to grow, posing threats of significant ecosystem damage (Boxes CC-OA and CC-CR). Nevertheless, defining those limits remains challenging owing to system complexity and lack of information regarding responses across different levels of biological organization (Steffen et al., 2009; Wookey et al., 2009; Lavergne et al., 2010; Preston et al., 2013a). Furthermore, species have mechanisms for coping with climate change including phenotypic plasticity (Charmantier et al., 2008; Matesanz et al., 2010), genetic (evolutionary) responses (Bradshaw and Holzapfel, 2006; Gienapp et al., 2008; Visser, 2008; Wang et al., 2013), and range shifts (Colwell et al., 2008; Thomas, 2010; Chen et al., 2011; see also Section 16.3.2.3). Such mechanisms influence adaptation limits by extending the range of climate conditions with which individual organisms can cope *in situ* and/or enabling species to migrate over time to more suitable climates. Yet, more comprehensive assessments of such adaptive mechanisms are needed to develop robust understanding of ecological limits.

While human systems may also experience hard limits, such systems are influenced by exogenous climate change as well as endogenous processes such as societal choices and preferences (Adger et al., 2009). This creates the potential for limits encountered by actors to be soft. Although they may limit adaptation for the current planning horizon, they may be ameliorated in the future by changing circumstances. Various authors have noted that adaptation limits are socially constructed by human agency in that economics, technology, infrastructure, laws and regulations, or broader social and cultural considerations can limit adaptation (*medium evidence*; *high agreement*; Adger et al., 2009; de Bruin et al., 2009b; Flåm and Skjærseth, 2009; O'Brien, 2009; Wilbanks and Kates, 2010; McNamara et al., 2011; Morrison and Pickering, 2012; see also Section 16.3). Cost-benefit analyses and associated discount rates, for example, reflect a social value on investment returns (Section 17.4.1). Yet, Morgan (2011) notes that adaptation planning based on cost-benefit analysis can pose limits to adaptation by discounting the future economic benefits of adaptation actions and excluding non-market benefits. Meanwhile, increasing loss and damage from societal exposure and climate change may pose financial limits to the insurability of disaster risks (Section 10.7.3), which ultimately influences what activities can occur in certain locations. All of these factors are dynamic and can change over time. The Shared Socioeconomic Pathways, which have been designed to facilitate comparison of findings across modeling teams, reflect different perspectives on future changes in the capacity of actors to adapt (Kriegler et al., 2012; Ebi et al., 2013; Schweizer and O'Neill, 2013; van Ruijven et al., 2013). Given rising incomes and advances in knowledge and technology, a greater number of adaptation options may become available to a greater number of actors over time. In contrast, impediments to development, constraints on investments in adaptation, or rapid escalations in risk may increase the likelihood of experiencing a limit.

Societal assessments of risk and willingness to invest in risk management are subject to many influences (Renn, 2008; IPCC, 2012; see also Section 14.5), such as experience of a recent disaster, some of which can result in rapid changes (Ho et al., 2008; Breakwell, 2010; Renn, 2011). Adger et al. (2009, p. 338) argue that many limits to adaptation are dependent on the changing goals, values, risk tolerances, and social choices of society which make them "mutable, subjective, and socially constructed." Similarly, Meze-Hausken (2008) views adaptation as being triggered in part by subjective thresholds including perceptions of change; choices, needs, and values; and expectations about the future (see also O'Brien, 2009). For instance, the distribution of grape suitability will change in response to climate change, but the potential for relocation as an adaptation is limited by the concept of "terroir," which reflects biophysical traits and local knowledge and wine making traditions to a cultural landscape (Box 23-1). However, terroir could become a soft limit if the rigid, regionally defined regulatory frameworks and concepts of regional identity that prescribe what grapes can be grown where were to become more geographically flexible and tied to the culture and history of the winemakers rather than regional climate and grape suitability (Box 23-1).

Limits also have scale-dependent properties (see also Section 16.3.2.10) (*limited evidence*, *high agreement*). Adaptation finance and capacity building activities more broadly, for example, enable resources for adaptation to be transferred from a variety of governmental and non-governmental entities to developing nations in order to overcome soft limits to adaptation (Section 16.3.2.5). For example, a local community may not have the necessary resources to adapt, but these constraints may be overcome by drawing in resources, such as technical expertise, from regional, national, or international authorities as well as from NGOs, other civil society organizations, or the private sector (Section 16.3.2.5). Scale dependence also manifests among different actors within sectoral supply chains. For example, climate change that poses limits to the sustainability of an individual farm enterprise may have less impact on a national or international agribusiness (Park et al., 2012).

16.4.2. Limits and Transformational Adaptation

Adaptation has traditionally been viewed as a process of incremental adjustments to climate variability and change to maintain existing objectives and values despite changes in climate conditions (Smit et al., 2001). As evidenced by the examples in Section 16.4.1, however, future changes in climate could exceed the capacity of human actors and/or natural systems to successfully adapt using incremental adjustments (*medium evidence*, *high agreement*). Since the AR4, the adaptation and resilience literature has suggested that climate change or other factors may drive actors toward the deliberate pursuit of transformational adaptation as a mechanism for managing the discontinuities associated with experiencing an adaptation limit (Pelling, 2010; Kates et al., 2012; O'Brien, 2012; O'Brien et al., 2012; O'Neill and Handmer, 2012; Dow et al., 2013a,b; see also Section 20.3). In addition, some studies have discussed the interactions between incremental and transformational adaptation and the pathways by which actors can transition from one to the other (Pelling, 2010; Park et al., 2012).

As a relatively new concept in the adaptation literature, clear operational definitions of what constitutes transformational adaptation remain elusive. Several authors have offered criteria that include a significant increase in the magnitude of a management effort; introduction of new technologies or practices; formation of new structures or systems of governance; or geographic shifts in the location of activities (Pelling, 2010; Stafford Smith et al., 2011; Kates et al., 2012; O'Neill and Handmer, 2012; Park et al., 2012; see also Sections 20.1, 20.5). However, the concept has also been identified as having normative elements involving changes in desired values, objectives, and perceptions of problems (Pelling, 2010; O'Neill and Handmer, 2012; O'Brien et al., 2012; Park et al., 2012). The current complexity and ambiguity in the definition of transformational adaptation may constrain its effective operationalization in policy environments (*very low confidence*). However, this matter has not been investigated.

In the context of limits to adaptation, transformational adaptation represents options and strategies that human actors can exploit to reorganize systems when incremental adaptation has reached its limits. As with incremental adaptation, these changes can be reactions to what has been experienced in the past or decisions made in anticipation of the future (Kates et al., 2012). As a fundamental change in a system, transformation may involve changes in actors' objectives and associated values. Therefore, transformational adaptation is not without risks or costs (Orlove, 2009; Kates et al., 2012; O'Brien, 2012). For example, the level of investment needed to relocate a community or economic enterprise to reduce the risk of system failure (Kates et al., 2012; O'Neill et al., 2012) and/or to take advantage of changing climatic conditions (Park et al., 2012) may be quite substantial. Furthermore, transformational adaptation may be associated with various externalities. Strategies such as migration, for example, may involve the loss of sense of place and cultural identity, particularly if migration is involuntary (Adger et al., 2009). The feasibility of transformational adaptation may therefore be dependent in part on whether it results in outcomes that are perceived to be positive versus negative (Preston and Stafford Smith, 2009). This suggests that the factors that constrain incremental adaptation (e.g., Section 16.3.2) also can constrain transformation, but the greater level of investment and/or shift in fundamental values and expectations required for transformational change may create greater resistance (*limited evidence*, *medium agreement*; Pelling, 2010; O'Brien, 2012; O'Neill and Handmer, 2012; Park et al., 2012).

16.5. Sectoral and Regional Synthesis

The adaptation literature since the AR4 indicates that despite a range of opportunities to enable adaptation, multiple factors will constrain adaptation planning and implementation (*very high confidence*; see Section 16.3), and, in some cases, such constraints may limit adaptation (*medium evidence*, *high agreement*; see Section 16.4). However, adaptation opportunities, constraints, and limits for adaptation vary significantly among different sectors and regional contexts (*very high confidence*; Adger et al., 2007; see also Sections 16.3-4; Table 16-3). This heterogeneity arises from a range of sources including regional differences with respect to the rate and magnitude of climate change that is experienced, differential exposure and sensitivity of sectors or ecological systems, and differential capacity to adapt. Given this diversity, it is important that opportunities, constraints, and limits are evaluated in the specific context in which they arise. Therefore, this section draws on the various assessments of adaptation presented in the sectoral (Chapters 3 to 13) and regional (Chapters 22 to 30) chapters of the WGII AR5 to synthesize knowledge regarding opportunities, constraints, and limits across these contexts.

16.5.1. Sectoral Synthesis

Each of the sectoral chapters in the WGII AR5 addresses the opportunities for, and constraints associated with, the pursuit of adaptation (Table 16-3). Collectively, this represents a rich body of knowledge regarding how adaptation processes are evolving among different human and natural systems. Although each sectoral chapter assesses the relevant literature on adaptation independently, common themes emerge (Table 16-3). Opportunities most often cited include building awareness, strengthening adaptive capacity, developing tools for improving vulnerability and risk assessments, and adopting favorable policies to improve governance. Likewise, common constraints arise among different sectors, but the bulk of the evidence for adaptation constraints is focused on inadequate governance and institutional structures at the scale of the challenge, lack of access to financial resources or relevant information for adaptation, and social and cultural norms that prevent adoption of viable adaptation options.

There are a number of emerging, integrated approaches to adaptation planning, governance, and implementation identified by many sectoral and regional chapters. For example, Integrated Water Resource Management (IWRM), Integrated Coastal Zone Management (ICZM), Community-Based Adaptation, and Ecosystem-Based Adaptation (EBA) are identified as cross-sectoral adaptation options, which are viewed as more effective than standalone efforts to reduce climate-related risks (Bijlsma et al., 1996; see also Sections 5.5.4, 14.3.2; Box CC-EA). Such integration is important, as many sectors experience threats not only from climate change, but also from a range of existing or emerging threats. The sectoral chapters also reflect on the distinction between autonomous adaptation, which is particularly important for natural systems such as freshwater, coastal, terrestrial, and ocean ecosystems (e.g., WGII AR5 Chapters 3 to 6), and planned adaptation, which features strongly in the literature associated with human-managed systems (WGII AR5 Chapters 5, 7 to 13).

Though the sectoral chapters offer few explicit definitions of adaptation limits, they reflect the potential for hard limits to be reached and the potential for them to be persistent due to interactions among multiple constraints (Section 16.3.2). For example, the sustainability of individual species or ecosystems may experience hard limits in a changing climate, as may ecosystem services for humans such as food crop and fisheries production. Though significantly more attention is given to sectoral adaptation opportunities, constraints, and limits than in the AR4, the AR5 chapters suggest that literature relevant to the coastal (Chapter 5), food systems (Chapter 7), and urban sectors (Chapter 8) has expanded more rapidly, perhaps because of the experience within these sectors with risk reduction planning associated with extreme weather events.

16.5.2. Regional Synthesis

While the regional chapters assess the relevant literature on key sectors affected by climate change, those discussions are specific to the various regional contexts (Table 16-3). Mainstreaming adaptation to climate change into national development policies, regional and local planning, and economic development has emerged as an opportunity across all regions for addressing multiple, interacting stresses (Dovers and Hezri,

Table 16-3 | Sectoral and regional synthesis of adaptation opportunities, constraints, and limits. Each icon represents types of opportunities, constraints, and limits (described below). The size of the icon represents when there is relatively little (small icon) or relatively ample (large icon) information in the sectoral and regional chapters to describe each type of opportunity, constraint, or limit. If no information was presented, the table cell is blank.

Opportunities *are defined as factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits*. Types of opportunities include (1) **Awareness**: communication, education, and awareness raising; (2) **Capacity**: human and institutional capacity building including preparedness, resource provision, and development of human and social capital; (3) **Tools**: decision making, vulnerability and risk analysis, decision support, and early warning tools; (4) **Policy**: integration and mainstreaming of policy, governance, and planning processes including sustainable development, resource and infrastructure planning, and design standards; (5) **Learning**: mutual experiential learning and knowledge management of climate vulnerability, adaptation options, disaster risk response, monitoring, and evaluation; and (6) **Innovation**: development and dissemination of new information, technology development, and technology application.

Constraints *are defined as factors that make it harder to plan and implement adaptation actions*. Types of constraints include (1) **Economic**: existing livelihoods, economic structures, and economic mobility; (2) **Social/cultural**: social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support; (3) **Human capacity**: individual, organizational, and societal capabilities to set and achieve adaptation objectives over time including training, education, and skill development; (4) **Governance**, Institutions & Policy: existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements, adaptive capacity, and absorption capacity; (5) Financial: lack of financial resources; (6) **Information**/Awareness/Technology: lack of awareness or access to information or technology; (7) **Physical**: presence of physical barriers; and (8) **Biological**: temperature, precipitation, salinity, acidity, and intensity and frequency of extreme events including storms, drought, and wind.

A ***Limit*** *is defined as the point at which an actor's objectives or system's needs cannot be secured from intolerable risks through adaptive actions*. Types of limits include (1) **Biophysical**: temperature, precipitation, salinity, acidity, and intensity and frequency of extreme events including storms, drought, and wind; (2) **Economic**: existing livelihoods, economic structures and economic mobility; and (3) **Social/cultural**: social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support.

Sectors

Sectors (chapter)	Opportunities: Awareness	Capacity	Tools	Policy	Learning	Innovation	Constraints: Economic	Human capacity	Social/cultural	Governance	Financial	Information	Physical	Biological	Limits: Economic	Social/cultural	Biophysical
Freshwater (3)	Small	Small	Small	Small	Small	Small	Small	Small	Small	Large	Large	Large	Small			Small	
Terrestrial (4)	Small	Small		Large		Small				Small	Small	Small	Large	Large			Small
Coastal (5)	Large	Large	Small	Large	Small		Small		Large	Large	Small	Small	Small	Large		Small	Large
Ocean systems (6)	Small		Small	Small							Small	Small	Small	Large			Large
Food systems (7)	Large	Large	Large	Large	Large	Large	Large		Small		Large	Large	Small	Small	Large		Large
Urban areas (8)	Small	Large	Large	Large	Large	Large	Large	Large	Large	Large	Large	Large	Large			Small	Small
Rural areas (9)	Small	Large	Small	Large	Small	Small	Small		Small	Small	Small	Small	Small		Small	Small	
Human health (11)	Small	Small	Small	Large		Small			Small	Small	Small	Large	Small		Small	Small	Small
Human security (12)				Small	Small		Small		Large	Large	Small	Large				Small	Small

Regions

Regions (chapter)	Opportunities: Awareness	Capacity	Tools	Policy	Learning	Innovation	Constraints: Economic	Human capacity	Social/cultural	Governance	Financial	Information	Physical	Biological	Limits: Economic	Social/cultural	Biophysical
Africa (22)	Large	Large	Large	Large	Large	Large	Small	Large	Large	Large	Large	Large				Small	Small
Europe (23)	Small		Small	Large		Small			Small	Large		Large			Small	Small	Large
Asia (24)		Small		Large	Large				Small	Large	Small			Small			Small
Australasia (25)	Small	Large	Small	Large				Small	Large	Large	Small	Large				Small	Small
North America (26)		Small	Small	Small				Small		Large	Large	Large	Small	Small			
Cental & South America (27)		Small		Large	Small		Small	Large	Small	Large	Small	Large					
Polar regions (28)		Small	Small		Large				Large	Small		Small	Small				Small
Small islands (29)	Small	Small	Small	Large	Small		Small	Small	Large	Large	Large	Large	Large				Small
Open oceans (30)		Small	Large	Large		Large				Large		Large					Large

Icon legend

Awareness, Capacity, Tools, Policy, Learning, Innovation, Economic, Human capacity, Social/cultural, Governance, Financial, Information, Physical, Biological, Biophysical

2010; Tompkins et al., 2010; Table 16-3). Most regional chapters reveal there are significant spatial and temporal mismatches between national adaptation planning on adaptation and local implementation to achieve substantive reductions in vulnerability. Adaptation interventions largely emphasize short-term risk management over long-term transformative strategic planning to reduce long-term risk, which potentially increases vulnerability and therefore the costs associated with future adaption efforts. Such short-sighted decision making can also create the potential for maladaptation (Barnett and O'Neill, 2010; Berrang-Ford et al., 2011; Preston et al., 2013b).

Effective governance and institutions for facilitating adaptation planning and implementation across multiple sectors within regions was by far the dominant opportunity and constraint. Both a shift to risk-based approaches to adaptation and to the multi-sector planning for adaptation mentioned previously (EBA, IRWM, and ICZM) offers opportunities for the development of approaches, tools, and guidelines for the construction of adaptation plans at a regional scale with a long-term focus. Developing and developed nations alike identified opportunities for building adaptive capacity and access to better information at the scale of decision making as important to making this happen. Compared with sectoral chapters, the regional chapters identified limits to adaptation less frequently (Table 16-3). This reflects the tendency for the literature to focus on limits for specific sectors, species, or ecosystems.

16.6. Effects of Mitigation on Adaptation Opportunities, Constraints, and Limits

The AR4 identified four ways in which adaptation and mitigation can interrelate, one of which is mitigation actions that have consequences for adaptation (Klein et al., 2007). It follows that mitigation actions could have consequences for adaptation constraints and limits. Klein et al. (2007) concluded that without mitigation, a magnitude of climate change could be reached that makes adaptation impossible for some natural systems, while for most human systems such high magnitudes of change would involve very high social and economic costs. Adaptation constraints and limits therefore have implications for the definition of dangerous anthropogenic interference under Article II of the UNFCCC (UNFCCC, 1992; see also Travis, 2010; Hoegh-Guldberg, 2011; Tao et al., 2011; Preston et al., 2013a). A number of studies published since the AR4, for example, demonstrate that constraining future greenhouse gas emissions would lower the magnitude of climate change experienced over the 20th century and constrain the magnitude of future adverse impacts or the likelihood of exceeding system thresholds (*very high confidence*; Stern et al., 2006; Preston and Jones, 2008; Sheehan et al., 2008; Meinshausen et al., 2009; O'Neill et al., 2010; Garnaut, 2011; Arnell et al., 2011; Rogelj et al., 2011; Webster et al., 2011; see also discussion of mitigation in the AR5 WGII sectoral and regional chapters). Therefore, mitigation can potentially reduce the magnitude of climate change to which human and natural systems must adapt.

Understanding the relationship between damages avoided by mitigation and adaptation limits requires information regarding what magnitude of climate change and associated damages would constitute an intolerable risk. The WGI contribution to AR5 quantifies the cumulative carbon dioxide (CO_2) emissions below which—with probabilities of >33%, >50%, and >66%—global mean warming would be limited to less than 2°C since the period 1861–1880 (see WGI AR5 Section12.5.4). Warming beyond 2°C is considered to give rise to "reasons for concern" (Smith et al., 2009a; see also Section 19.6), in part because adaptation to impacts associated with such warming would be constrained or limited (Sections 16.3.2, 16.4.1; Box 16-3). Uncertainty about the location of both hard and soft limits is due to the fact that these limits are determined not only by the degree and rate of climate change (as a function of mitigation pathways), but also by the degree and rate of non-climatic stresses affecting the resilience or adaptive capacity of natural and human systems (Section 16.4). Little empirical information is available on the functional relationships between climate change, non-climatic stresses, and the emergence of limits to adaptation. The literature aiming to establish at which degree and rate of climate change, or at which levels of mitigation, such adaptation constraints and limits emerge is sparse and refers primarily to natural systems (*limited evidence*, *medium agreement*; Section 16.4).

Frequently Asked Questions

FAQ 16.3 | How does greenhouse gas mitigation influence the risk of exceeding adaptation limits?

There is *very high confidence* that higher rates and/or magnitudes of climate change contribute to higher adaptation costs and/or the reduced effectiveness of certain adaptation options. For example, increases in global mean temperature of 4°C or more would necessitate greater investment in adaptation than a temperature increase of 2°C or less. As future climate change is dependent on emissions of greenhouse gases, efforts to mitigate those emissions can reduce the likelihood that human or natural systems will experience a limit to adaptation. However, uncertainties regarding how future emissions translate into climate change at global and regional levels remain significant, and therefore it is difficult to draw robust conclusions regarding whether a particular greenhouse gas stabilization pathway would or would not allow residual risk to be successfully managed through adaptation. For example, evidence regarding limits to adaptation does not substantiate or refute the idea that an increase in global mean temperature beyond 2°C represents an adaptation limit or, subsequently, "dangerous anthropogenic interference" as defined by the UNFCCC's Article II.

Nevertheless, studies indicating that limits to adaptation have already been reached for some systems suggest the climate change observed to date has been sufficient to threaten the sustainability of human communities, ecosystem services, or ecological systems (*limited evidence*, *medium agreement*; Section 16.4). For many valued human and natural systems, the complex spatial and temporal dynamics of impacts, adaptive capacity, and adaptation make it difficult to quantitatively project with any degree of accuracy and confidence when and where limits to adaptation will be encountered. Furthermore, although constraints and limits have been demonstrated to have cross-scale and cross-level interactions (Sections 16.3.2.10, 16.4.1), there is little evidence that indicates how limits to adaptation experienced by actors, species, or ecosystems in individual regions or sectors scale to a global aggregate limit. Therefore, there is little evidence to either substantiate or refute the idea that global mean warming beyond 2°C represents a global adaptation limit.

Analysis by Christensen et al. (2011) (see also WGI AR5 Section 12.4.1) shows that all emission scenarios—whether aggressive mitigation scenarios consistent with a 2°C stabilization pathway or medium-high emission scenarios such as *Special Report on Emission Scenarios* (SRES) A1B and A1Fi, or Representative Concentration Pathway 6.0 (RCP6.0) and RCP8.5—are very similar in terms of projected climate up to 2040 (i.e., the "era of climate responsibility"). The effects of mitigation on overall adaptation potential will therefore arise in the medium to long term, during the "era of climate options." Integrated Assessment Models (IAMs) can assess the relative damage-reducing effect of mitigation and adaptation, based on the assumption that the two strategies are substitutes. In reality, however, mitigation and adaptation are hardly substitutable: they create benefits on different spatial, institutional and temporal scales and involve different actors with different interests. Substitutability of mitigation and adaptation in IAMs requires the reconciliation of welfare impacts on people living in different places and at different points in time into an aggregate measure of well-being (Klein et al., 2007). Moreover, defining the costs and benefits of adaptation is particularly difficult, limited by data, and depends on value judgments (Chapter 17).

Since AR4 the literature on tipping elements (Lenton et al., 2008; Kriegler et al., 2009; Levermann et al., 2012) has provided a greater separation of mitigation and adaptation, because only mitigation can avoid these discontinuities. While there could be potential for mitigation and adaptation substitutability under scenarios where catastrophic climate change is avoided, the thresholds for the onset of any tipping elements (anticipated to drive some systems to the limits of adaptation) are not known. These concerns have been picked up in the economic literature, in relation to the plausible, if unknown, probability of catastrophic climate change as well as "fat tails," where uncertainty is so large that the tails of the probability distribution tend to dominate (Weitzman, 2009). Against this background, mitigation can prevent or delay catastrophic climate change and the reaching of adaptation limits.

Several studies using IAMs have investigated tradeoffs between mitigation and adaptation (de Bruin et al., 2009a; Bosello et al., 2010), treating the two strategies as substitutes in order to find a balance or even an optimal mix. De Bruin et al. (2009a) report that short-term optimal policies need to consist of a mixture of substantial investments in adaptation measures, coupled with investments in mitigation, even though the latter will decrease damages only in the longer term. They also find that the relative mix of the two depends critically on the assumptions, notably in relation to discount rate and the parameterization of damages. Felgenhauer and de Bruin (2009) examine the role that uncertainty over climate sensitivity has on optimal mitigation and adaptation policy levels over time. They find that optimal levels of both mitigation and adaptation are lower under uncertainty than under certainty, and that the optimal mitigation level is more dependent on adaptation costs than vice versa.

Such findings are all preliminary, because the current representation of adaptation in IAMs is generally very simple (Ackerman et al., 2009; Patt et al., 2010b). The models adopt a highly aggregated and theoretical approach without considering any real-world constraints on adaptation (Ackerman et al., 2009; Patt et al., 2010b). They also often assume perfect foresight, no uncertainty, and no maladaptation (see also Watkiss, 2011; Berkhout, 2012). More recent models have attempted to address some of these issues. De Bruin and Dellink (2011), for example, model different types of constraints of adaptation over time. Also the PAGE09 model assumes adaptation to be about half as effective as it was in PAGE02 (Hope, 2011). Along with other factors, the reduced effectiveness of adaptation in the model leads to a strong increase in the economic costs of climate change (Hope, 2011).

16.7. Ethical Dimensions of Adaptation Opportunities, Constraints, and Limits

Hartzell-Nichols (2011, p. 690) argues that, in general terms, "Adaptation is fundamentally an ethical issue because the aim of adaptation is to protect that which we value." More specifically, ethical issues concern the distribution of costs and benefits of prevention measures and adaptation activities, compensation for residual damages, and participation in the related decision processes (Grasso, 2009). These distributive and procedural justice-related issues can be diverse and contextually specific (Paavola, 2011). Brisley et al. (2012) argue that ensuring social justice in adaptation requires both an understanding of which groups are most vulnerable to climate change impacts, as well as social choice processes about adaptation responses that are seen to meet the needs of the vulnerable fairly. The key ethical issues raised by adaptation opportunities, constraints, and limits as they are discussed here are summarized in Table 16-4, together with the public policy questions they raise.

Defining general moral principles to clarify how to handle risks to objectives, values, and needs, including where they are unavoidable and catastrophic, is difficult. According to Gardiner (2006, p. 407), "Even our best theories face basic and often severe difficulties addressing basic issues … such as scientific uncertainty, intergenerational equity, contingent persons, nonhuman animals, and nature. But climate change involves all of these matters and more."

Complicating this picture further is the observation that social and personal values are not universal or static (O'Brien, 2009; O'Brien and Wolf, 2010). There may be different, but equally legitimate, values that are fostered or put at risk by climate change (Adger et al., 2012). These are not limited to instrumental or economic values, but include cultural

Table 16-4 | Ethical dimensions of adaptation opportunities, constraints, and limits and their policy implications.

	Ethical dimensions	Commentary	Public policy issues	References
Adaptation opportunities	Access to opportunities	Inequitable access to the factors that make it easier to adapt and achieve adaptation objectives	Whether national or international policy should support more equitable access to adaptation opportunities	Thomas and Twyman (2005); Paavola and Adger (2006); Paavola (2008); Füssel (2010); Rübbelke (2011); Klinsky et al. (2012)
Adaptation constraints	Distribution of constraints	Inequitable distribution of factors that make it harder to plan and implement adaptation actions	Whether national or international policy should reduce or remove constraints to adaptation	Paavola and Adger (2006); Klein and Möhner (2009); Grasso (2010)
Adaptation limits	Differing attitudes to risk	What is deemed an acceptable, tolerable, and intolerable risk will vary across cultures, social groups, and individuals.	Risk governance is concerned with balancing differentiated and dynamic attitudes to risk in allocating resources to managing risks.	Bisaro et al. (2010); Juhola et al. (2011); Lata and Nunn (2012); Sovacool (2012); Fatti and Patel (2013); Ward et al. (2013)
	Rights and potentials of people to secure particular valued objectives	Limits are related to given valued objectives, but such objectives vary between individuals and collectives.	Risk governance related to adaptation limits is concerned with setting priorities between different (and conflicting) valued objectives.	Foale (2008); Devine-Wright (2009); Gorman-Murray (2010); Jacob et al. (2010); Brown et al. (2011); Adger et al. (2012)
	Differing rates at which limits are reached	Limits will be reached earlier by some groups and regions (Arctic, unprotected coastal zones) than others.	Risk governance at different scales will be confronted with choices about adaptation limits emerging through time.	Baum and Easterling (2010); Edvardsson-Bjornberg and Hansson (2011); Dow et al. (2013a)
	Trade-offs in securing valued objectives	Adaptive responses will involve choices between valued objectives at adaptation limits (i.e., between river water quality and water demand from irrigation).	As adaptation limits that affect multiple valued objectives are reached, private and public choices will be made about which values have priority over others.	Steenberg et al. (2011); Towler et al. (2012); Pittock (2013); Seidl and Lexer (2013)
	Intergenerational and interspecies equity and adaptation limits	Valued objectives may be irrecoverably lost at adaptation limits, denying them to future generations.	Species extinctions and loss of cultural heritage, place, or identity may call for extraordinary public policy interventions.	Albrecht et al. (2013)

values as well. Berkes (2008, p. 163), for instance, documents that in Inuit culture, the loss of sea ice in summer months leaves some people "lonely for the ice." Whether the risk of irreversible cultural losses would be seen as intolerable remains a complicated question, but has been noted to manifest in a psychological response termed "solastalgia" (Albrecht et al., 2007). The loss of traditional ways of experiencing and seeing the world is a common occurrence throughout human history. The ethical question is whether such losses should be acknowledged in considering adaptation opportunities, constraints, and limits (as well as in human responses to climate change more generally).

One ethical principle that is widely applied in ethical discussions of climate is "equity" (Gardiner, 2010). It is now well established that nations, peoples, and ecosystems are differentially vulnerable to current and future projected climate change impacts, which themselves are unequally distributed across world regions (*very high confidence*; IPCC, 2007b; Füssel, 2009, 2010). This inequity is exacerbated by the fact that exposure to adverse impacts is involuntary for many societies (Paavola and Adger, 2006; Patz et al., 2007; Dellink et al., 2009; Füssel, 2010). Thus, adaptation constraints have the potential to create or exacerbate inequitable consequences due to climate change (*very high confidence*). Where limits to adaptation lead to catastrophic losses there is often a need for humanitarian responses, as well as more structural adaptations at the societal level (*medium evidence*, *high agreement*; Bardsley and Hugo, 2010). Linked to this is the complex question of the attribution of risks to anthropogenic forcing of climate change and whether there could be grounds for redress or compensation (Verheyen, 2005). In this regard, different ethical positions taken by countries such as through "equity weighting" would result in very different compensation outcomes (Anthoff and Tol, 2010).

Inequity resulting from adaptation constraints and limits emerge across several dimensions: inter-country equity, inter-generational equity, inter-species equity (Schneider and Lane, 2006b), and intra-country or sub-national equity (Thomas and Twyman, 2005). Climate change, and the need for adaptation, unfairly shifts burdens onto future generations, contradicting the principle of intergenerational equity. This raises ethical and justice questions because benefits are extracted from the global environment by those who do not bear the burden of that extraction (UNEP, 2007). Policy debates about intergenerational equity considerations have been dominated by the need to treat the time discount rate consistently across cases (Nordhaus, 2001; Stern et al., 2006; Beckerman and Hepburn, 2007). But this debate largely ignores the challenge of irreversible damages associated with limits to adaptation, especially those that may result from nonlinear damage functions (Hanemann, 2008). Inter-species equity is the subject of an evolving ethics debate (e.g., Jolibert et al., 2011), but adaptation interventions involving ecosystems and wild species increasingly invoke human and societal benefits as a primary motivation (CBD, 2009; Box CC-EA).

Law codifies the social values and objectives influenced by opportunities, constraints, and limits to adaptation, and sets norms and procedures for dealing with problems of risk and loss, including the intolerable losses experienced at adaptation limits (Section 16.3.2.8). Changing such values and objectives, including the shifting and sharing of risks this may involve, will often involve complex and time-consuming governance effort. National and international law will play a role in managing and sharing climate-related risks. The Cancun Adaptation Framework (UNFCCC, 2011) adopted at COP16 of the UNFCCC sets out principles for international cooperation on adaptation "…to enable and support the implementation of adaptation actions" (UNFCCC, 2010,

p. 4). Nevertheless, the complexity of international law comprises a significant constraint to making the case for addressing the breaching of adaptation limits (Koivurova, 2007). At national and subnational levels, cultural attitudes can contribute to stakeholder marginalization from adaptation processes (Section 16.3.2.7), thus preventing some constraints and limits from being identified (such as gender issues and patriarchal conventions).

16.8. Seizing Opportunities, Overcoming Constraints, and Avoiding Limits

As discussed in this chapter, researchers and practitioners now have a richer understanding of how constraints and limits influence adaptation (Sections 16.3-7). Based on the available literature, however, less attention has been paid to understanding the range of opportunities that exist and how they create enabling conditions for adaptation (Section 16.3.1; Table 16-1). Focused research on facilitating such enabling conditions and how these lead to the minimization or avoidance of adaptation constraints would support capacity building of individuals and institutions (*very high confidence*; Smith et al., 2008; Ford, 2009; Burch, 2010; Ford et al., 2010; Eisenack, 2012; Biesbroek et al., 2013a). Translating knowledge of potential opportunities into adaptation responses requires that they be recognized and then exploited by actors. Such opportunities are being created through policies, tools, and guidelines that are emerging throughout the developed and developing world (Sections 15.2, 16.3.2.1). It is not yet clear if these efforts are translating into effective adaptation actions for the benefit of human and natural systems including the avoidance of limits. As adaptation practice has focused on what adaptation efforts can achieve in terms of avoided damages rather than on the residual damages that adaptation cannot avoid (Jenkins et al., 2011; McNamara et al., 2011), this question remains largely unexplored.

Adaptation constraints have contributed to uneven adaptation planning and implementation, with some sectoral and regional actors progressing more rapidly than others (*very high confidence*; Urwin et al., 2008; Biesbroek et al., 2010; Tompkins et al., 2010; Bichard and Kazmierczak, 2012; Bierbaum et al., 2012; Carmin et al., 2012). Multiple studies have concluded that adaptation is largely proceeding autonomously and incrementally, often in response to perceived climate change trends and impacts that have been experienced (*medium evidence*, *high agreement*; Ford, 2009; Ford et al., 2010, 2011; Berrang-Ford et al., 2011; Preston et al., 2011a; Lesnikowski et al., 2013). In so doing, however, actors may not adequately invest in adaptation responses that will address future long-term risks associated with higher levels of climate change (*limited evidence*, *medium agreement*; Preston et al., 2013b; see also Section 16.3.2.2). The suggestion that incremental approaches to mitigation and adaptation may be inadequate to avoid intolerable risks has led to a growing discourse regarding transformational adaptation (Pelling, 2010; Kates et al., 2012; O'Brien, 2012; O'Neill and Handmer, 2012; Park et al., 2012). While various practical examples of transformational adaptation appear in the literature (Kates et al., 2012; O'Neill and Handmer, 2012; Park et al., 2012; see also Section 16.4.2), the extent to which transformational adaptation can be operationalized within adaptation policy remains unclear. Unresolved issues including which actors, sectors, and regions should be considering transformational adaptations, when, and what constitutes appropriate adaptation actions under such circumstances would benefit from focused investigation.

Better understanding and quantification of how future GHG emissions trajectories and climate change translates into impacts would improve understanding of limits to adaptation. Fundamental understanding of the vulnerability of different regions and sectors to climate change suggest that adaptive capacity is finite and thus, in general, limits to adaptation can be anticipated to arise as a consequence of future global change (*medium evidence*, *high agreement*; Sections 16.3.2, 16.4-6). Yet, at present, understanding of limits to adaptation is largely qualitative, and it is unclear whether current approaches to assessing climate change impacts and adaptation sufficiently explore the range of potential future climates and adaptive capacities of human and natural systems in a manner that is sufficient to identify limits. The parallel process for scenario development may provide a coherent framework for internally consistent analyses of climate change impacts that address uncertainty among climate models, emissions scenarios, and socioeconomic scenarios (Moss et al., 2010; van Vuuren et al., 2012; Ebi et al., 2013). Such knowledge could subsequently provide early warning of systems at risk of experiencing intolerable risks (Dow et al., 2013a,b) while also providing guidance regarding GHG mitigation targets.

Finally, recent literature questions whether existing institutions and systems of governance are adequate to effectively manage climate change risk. This includes not only institutions engaging in adaptation planning and implementation (Berkes and Armitage, 2010; Chapin et al., 2010; National Research Council, 2010; UKCIP, 2011; Kates et al., 2012; Biesbroek et al., 2013a), but also those associated with adaptation research (Meyer, 2011; Kates et al., 2012). New institutions and institutional arrangements have in fact emerged including adaptation research institutions with boundary spanning functions (Preston et al., 2013c; see also Section14.2.3), as well as those designed to facilitate adaptation and improve environmental and risk management (*medium evidence*, *high agreement*; National Research Council, 2009; Biesbroek et al., 2011; Jäger and Moll, 2011; Lemos et al., 2013). However, others have cautioned that the complexity of modern governance systems poses significant constraints on institutional change (Adger et al., 2009; see also Section 16.3.2.8), and new institutions do not necessarily resolve complex governance challenges (Lebel et al., 2013). Additional research is therefore needed regarding the extent to which new institutions will be required to effectively govern adaptation.

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17

Economics of Adaptation

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Frequently Asked Questions

17.1: Given the significant uncertainty about the effects of adaptation measures, can economics contribute much to decision making in this area? 954

17.2: Could economic approaches bias adaptation policy and decisions against the interests of the poor, vulnerable populations, or ecosystems? 961

17.3: In what ways can economic instruments facilitate adaptation to climate change in developed and developing countries? 965

17

Executive Summary

In the presence of limited resources and a range of objectives, adaptation strategy choices involve trade-offs among multiple policy goals (*high confidence*). The alternative policy goals include development and climate change mitigation. Economics offers valuable insights into these trade-offs and into the wider consequences of adaptation. It also helps to explain the differences between the potential of adaptation and its achievement as a function of costs, barriers, behavioral biases, and resources available. {17.2.7.1-2, 17.3.1}

Economic thinking on adaptation has evolved from a focus on cost-benefit analysis and identification of "best economic" adaptations to the development of multi-metric evaluations including the risk and uncertainty dimensions in order to provide support to decision makers (*high confidence*). Economic analysis is moving away from a unique emphasis on efficiency, market solutions, and cost-benefit analysis of adaptation to include consideration of non-monetary and non-market measures, risks, inequities and behavioral biases, and barriers and limits and consideration of ancillary benefits and costs. One role of economics is to contribute information to decision makers on the benefits and costs, including a number of non-monetary items, and on the equity impacts of alternative actions. It does not provide a final ranking for policy makers. A narrow focus on quantifiable costs and benefits can bias decisions against the poor and against ecosystems and those in the future whose values can be excluded or are understated. Sufficiently broad-based approaches, however, can help avoid such maladaptation. Indeed the evidence shows that maladaptation is a possibility if the evaluation approaches taken are not comprehensive enough in this sense. {17.2.3, 17.3.2}

The theoretical basis for economic evaluation of adaptation options is clear, and can be and has been applied to support decisions in practical contexts (*medium confidence*). There is extensive experience of applying the concepts and methods underlying the economic framework in non-adaptation contexts, which is useful for designing climate adaptation policies. The limited empirical evidence available shows a number of cases where desirable adaptation strategies have been identified based on these economic tools. The findings show that adaptation is highly regional and context specific. Thus the results do not readily permit widespread generalizations about the nature of attractive adaptation actions. {17.2, 17.4.1-2, 17.4.4}

Both private and public sectors have a role to play in the development and implementation of adaptation measures (*high confidence*). Economic theory and empirical results show that a degree of adaptation will be autonomously carried out by private parties in response to climate change. However, the private sector alone will often not provide the desirable level of adaptation with some types of actions not undertaken due to costs, incentives, nature of beneficiaries, and resource requirements. This implies the public sector will need to play a strong role. There are also other reasons for public action such as overcoming barriers, developing technologies, representing current and future equity concerns, and other items. {17.2.1, 17.3.1}

The theory and the evidence indicate that adaptation cannot generally overcome all climate change effects (*high confidence*). In addition to there being biophysical limits to adaptation, such as the inability to restore outdoor comfort under high temperatures, some adaptation options will simply be too costly or resource intensive or will be cost ineffective until climate change effects grow to merit investment costs. Thus the desirability of adaptation options will vary with time and climate change realization. {17.2.2, 17.2.5}

Adaptation generally needs to be seen in the frame of the overall development path of the country, particularly for developing countries (*high confidence*). Development and adaptation can be complementary or competitive. Also development can yield positive ancillary adaptation effects or co-benefits, provided it takes into account climate change in its design. Adaptation actions can provide significant co-benefits such as alleviating poverty or enhancing development. Many aspects of economic development also facilitate adaptation to a changing climate, such as better education and health, and there are adaptation strategies that can yield welfare benefits even in the event of a constant climate, such as more efficient use of water and more robust crop varieties. Maximizing these synergies requires a close integration of adaptation actions with existing policies, referred to as "mainstreaming." {17.2.7, 17.2.3.1-2}

Not all adaptation actions are investment-based. Policy actions are also important tools for adaptation (*medium confidence*). These include direct research & development (R&D) funding, environmental regulation, economic instruments, and education. Economic instruments have high potential as flexible tools because they directly and indirectly provide incentives for anticipating and reducing impacts and can have lower costs in the public budget. These instruments are currently not well explored in an adaptation context apart from risk financing instruments. Existing incentives will lead to a set of private adaptation actions. They include risk sharing and transfer mechanisms (insurance), loans, public-private finance partnerships, payment for environmental services, improved resource pricing (water markets), charges and subsidies including taxes, norms and regulations, and behavioral modification approaches. These instruments offer some useful possibilities for addressing climate change but they also have problems of effective implementation that need to be addressed. The problems can be particularly severe in developing countries. {17.4-5}

Risk financing mechanisms at local, national, regional, and global scales contribute to increasing resilience to climate extremes and climate variability, but involve major design challenges so as to avoid providing disincentives, causing market failure and worsening equity situations (*medium confidence*). Mechanisms include insurance; reinsurance; micro insurance; and national, regional, and global risk pools. The public sector often plays a key role as regulator, provider, or insurer of last resort. Risk financing can directly promote adaptation through providing claim payments after an event and allow for improved decisions under risk pre-event (strong evidence). It can also directly provide incentives for reducing risk, yet the evidence is weak and the presence of many counteracting factors often leads to disincentives, which is known as moral hazard. {17.5.1}

Limited evidence indicates a gap between global adaptation needs and the funds available for adaptation (*medium confidence*). There is a need for a better assessment of global adaptation costs, funding, and investment. Studies estimating the global costs of adaptation are characterized by shortcomings in data, methods, and coverage (*high confidence*). {14.2, 17.4; Tables 17-2, 17-3}

Economics offers a range of techniques appropriate for conducting analysis in the face of uncertainties, and the choice of the most appropriate technique depends on the nature of the problem and the nature and level of uncertainty (*high confidence*). Uncertainty is unavoidable in analyses of adaptation to climate change because of lack of data, the efficacy of adaptation actions, and uncertainties inherent in forecasting climate change. Approximate approaches are often necessary. There is a strong case for the use of economic decision making under uncertainty, working with tools such as cost-benefit and related approaches that include time dimensions (real options techniques), multi-metrics approaches, and non-probabilistic methodologies. There are methodologies that are able to capture non-monetary effects and distributional impacts, and to reflect ethical considerations. {17.3.2.1-3}

Selected regional and sectoral studies suggest some core considerations and characteristics that should be included in the economic analyses of adaptation (*medium confidence*). These desirable characteristics include a broad representation of relevant climate stressors to ensure robust economic evaluation; consideration of multiple alternatives and/or conditional groupings of adaptation options; rigorous economic analysis of costs and benefits across the broadest possible market and non-market scope; and a strong focus on support of practical decision making that incorporates consideration of sources of uncertainty. Few current studies manage to include all of these considerations. {17.4.3}

17.1. Background

This chapter assesses the literature on the economics of climate change adaptation, building on the Fourth Assessment Report (AR4) and the increasing role that economic considerations are playing in adaptation decision making and policy. AR4 provided a limited assessment of the costs and benefits of adaptation, based on narrow and fragmented sectoral and regional literature (Adger et al., 2007). Substantial advances have been made in the economics of climate change adaptation after AR4.

The specific objectives involved in an adaptation effort can be diverse. One may try to cancel all impacts (negative and positive), maintaining the status quo. Alternatively one can try to cancel adverse impacts and capture positive opportunities, so that the welfare gain (or loss) is maximized (or minimized).

Part of the literature presents adaptation as a continuous, flexible process, based on learning and adjustments (see, e.g., IPCC, 2012). Adaptation projects informed by this approach emphasize learning and experimenting, plus the value of using reversible and adjustable strategies (Berkhout et al., 2006; McGray et al., 2007; Pelling et al., 2007; Leary et al., 2008; Hallegatte, 2009; Hallegatte et al., 2011c).

Adaptation action and policy has also advanced since AR4, and the literature on the economics of adaptation has reflected this. This chapter builds on other chapters in this assessment—in particular Chapter 2, which sets the basis for decision making, recognizing economics as a decision support tool for both public and private actors. The type of economic approach used depends on factors discussed in Chapter 2, among others, including the agent making the decision, the nature or type of decision, the information used to make the decision, who implements the decision, others affected by the outcomes, and the values attached to those outcomes. While realizing the linkages between adaptation and mitigation, the starting point of this chapter is that adaptation is a given need.

This chapter assesses the scientific literature covering the economic aspects of adaptation; decision making and the economic context of adaptation, including economic barriers to adaptation decision making, and uncertainty; costing adaptation; and the economic and related instruments to provide incentives for adaptation.

17.2. Economic Aspects of Adaptation

When considering adaptation, economic studies give insight into issues regarding the roles of various actors in society, the character of adaptation strategies, the types of benefits and costs involved, the role of time, and a number of other factors that we discuss in this section.

17.2.1. Public and Private Actors in Adaptation Implementation

Previous IPCC reports—i.e., the Third Assessment Report (TAR) and First Assessment Report (FAR)—indicate adaptation actions can be autonomous, planned, or natural. Autonomous actions are undertaken mostly by private parties while planned can be undertaken by private or public actors. Natural adaptation is that occurring within the ecosystem in reaction to climate change but may be subject to human intervention (see discussion in Section 14.1).

In terms of human actions there are important economic distinctions regarding the roles of private and public actors. Some adaptation actions create public goods that benefit many and in such cases the implementing party cannot typically capture all the gains. For example, if an individual pays to protect a coastline or develop an improved irrigation system, the gains generally go to many others. Classical economic theory (Samuelson, 1954) and experience plus observations regarding adaptation (Mendelsohn, 2000; Osberghaus et al., 2010a; Wing and Fisher-Vanden, 2013) indicate that such actions will not receive appropriate levels of private investment (creating a market failure). In turn, this calls for public action by elements of broader society (e.g., governments, non-governmental organizations (NGOs), or international organizations).

Other reasons for public provision or public regulation of certain adaptation measures that lead to less than a socially desirable level of adaptation are discussed in Section 17.3.

17.2.2. Broad Categorization of Adaptation Strategies

There are many possible adaptation measures, as indicated in the TAR and FAR, plus Chapters 14 and 15. In economic terms these include a mixture of public and private actions taken in both domestic and international settings. A broad characterization of these and who might undertake them follows:

- Altered patterns of enterprise management, facility investment, enterprise choice, or resource use (mainly private)
- Direct capital investments in public infrastructure (e.g., dams and water management—mainly public)
- Technology development through research (e.g., development of crop varieties—private and public)
- Creation and dissemination of adaptation information (through extension or other communication vehicles—mainly public)
- Human capital enhancement (e.g., investment in education—private and public)
- Redesign or development of adaptation institutions (e.g., altered forms of insurance—private and public)
- Changes in norms and regulations to facilitate autonomous actions (e.g., altered building codes, technical standards, regulation of grids/networks/utilities, environmental regulations—mainly public)
- Changes in individual behavior (private, with possible public incentives)
- Emergency response procedures and crisis management (mainly public).

Not all adaptation involves investment or is costly. Some adaptation measures involve modification of recurring expenditures as opposed to new investments (replacing depreciated equipment with more adapted items). Sometimes adaptation involves changes in behaviors and lifestyles (e.g., due to increased frequency of heat waves).

17.2.3. Broad Definition of Benefits and Costs

The consequences of adaptation decisions cannot be expressed comprehensively through standard economic accounting of costs and revenues. Adaptation decisions can also affect other items such as income distribution and poverty (Jacoby et al., 2011); the regional distribution of economic activity, including employment; non-market factors such as water quality, ecosystem function, and human health; and social organization and cultural practices.

Adaptation choices have broad ranging and complex impacts on such issues as:

- Macroeconomic performance (see, e.g., Fankhauser and Tol, 1995)
- Allocation of funds with a crowding out effect on other climate and non-climate investments with consequences for future economic growth (Hallegatte et al., 2007; Hallegatte and Dumas, 2008; Wang and McCarl, 2013)
- Welfare of current and future generations through resource availability and other non-monetary effects
- Risk distributions on all of the above due to routine variability plus uncertain estimates of the extent of climate change and adaptation benefits and costs.

A number of these items pose challenges for measurement and certainly for monetization. Generally this implies that any analysis be multi-metric, with part in monetary terms and other parts not, and some in precise quantitative terms and others not (for more discussion see Section 17.3). In view of this, it is reasonable to conclude that an unbiased, comprehensive analysis would consist of a multi-metric analysis encompassing cost-benefit and other monetary items plus non-monetary measures. That analysis would support adaptation decision making.

17.2.3.1. Ancillary Economic Effect of Adaptation Measures and Policies

In addition to creating an economy that is more resilient to the effects of climate change, adaptation strategies often have ancillary effects of substantial importance. These can be positive (co-benefits) or negative (co-costs). Ancillary effects also arise when actions aimed primarily at mitigation or non-climate-related matters alter climate adaptation. Examples include:

- Sea walls that protect against sea level rise and at the same time protect against tsunamis. However, they can have co-costs causing damages to adjacent regions, fisheries, and mangroves (Frihy, 2001).
- Crop varieties that are adapted to climate change have enhanced resistance to droughts and heat and so also raise productivity in non-climate change-related droughts and temperature extreme (Birthal et al., 2011).
- Better building insulation that mitigates energy use and associated greenhouse gas emissions also improves adaptation by protecting against heat (Sartori and Hestnes, 2007).
- Public health measures that adapt to increases in insect-borne diseases also have health benefits not related to those diseases (Egbendewe-Mondzozo et al., 2011).
- More efficient use of water—adaptation to a drier world—will also yield benefits under current conditions of water scarcity. Development of improved desalination methods has the same merits (Khan et al., 2009).
- Locating infrastructure away from low-lying coastal areas provides adaption to sea level rise and will also protect against tsunamis.
- Reducing the need to use coal-fired power plants through energy conserving adaptation will also provide mitigation, improve air quality, and reduce health impacts (Burtraw et al., 2003).

17.2.3.2. Economic Consideration of Ancillary Effects

Many studies argue that co-benefits should be factored into decision making (e.g., Brouwer and van Ek, 2004; Ebi and Burton, 2008; Qin et al., 2008; de Bruin et al., 2009a; Kubal et al., 2009; Viguie and Hallegatte, 2012). If a country has a fixed sum of money to allocate between two competing adaptation projects, and both strategies generate net positive ancillary effects, then the socially optimal allocation of adaptation investment will differ from the private optimum and will favor the activity with the larger direct plus ancillary effects.

17.2.4. Adaptation as a Dynamic Issue

Adaptation is not a static concern. Rather it evolves over time in response to a changing climate (Hallegatte, 2009). Adaptation is perhaps best handled via a long-term transitional, continuous, flexible process that involves learning and adjustment (Berkhout et al., 2006; McGray et al., 2007; Pelling et al., 2007; Leary et al., 2008; Hallegatte, 2009; Hallegatte et al., 2011c; IPCC, 2012). Generally the literature indicates that optimal adaptation and the desirability of particular strategies will vary over time depending on climate forcing plus other factors such as technology availability and its maturity (de Bruin et al., 2009b). In the next few decades, during which time projected temperatures do not vary substantially across socioeconomic/climate scenarios, adaptation is the main economic option for dealing with realized climate change. Risk is also an important aspect, with the longer term being more uncertain that the near term. Risk-sensitive decisions often include the options of acting or of waiting (Linquiti and Vonortas, 2012). The issue of options is discussed further in Beltratti et al. (1998), which covers uncertainty about future preferences through option values.

Dynamics also are involved with strategy persistence owing to the decadal to century time scale implications of some adaptation strategies such as construction of seawalls or discovery of drought-resistant crop genes. The desirability of investments with upfront costs and persistent benefits increases when the benefits are long lasting or when climate change damages accumulate slowly (Agrawala et al., 2011; de Bruin, 2011; Wang and McCarl, 2013). However, maladaptation effects rising over time are also possible as protecting now can expand investment in vulnerable areas and worsen future vulnerability (Hallegatte, 2011).

17.2.5. Practical Adaptation Strategy Attractiveness and Feasibility

Adaptation cannot reasonably overcome all climate change effects (Parry et al., 2009). A number of factors will limit strategy adoption and

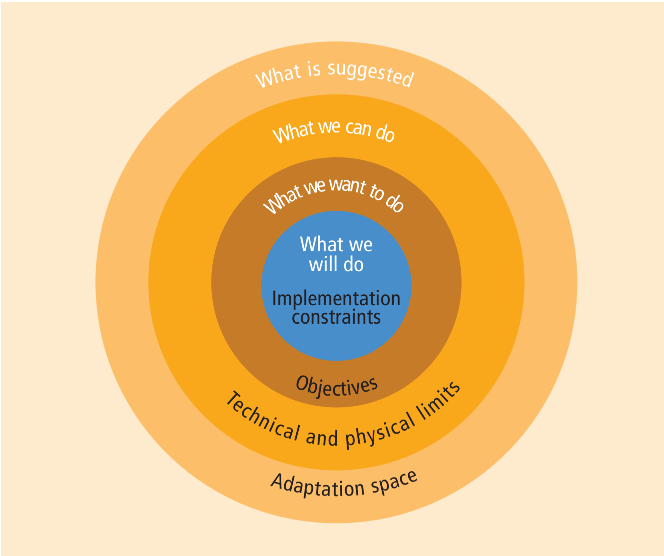

Figure 17-1 | The narrowing of adaptation from the space of all possible adaptations to what will be done. Forces causing the narrowing are listed in black.

preclude elimination of all climate change effects. A conceptual way of looking at this for a given adaptation endeavor is in Figure 17-1. The first outside circle represents the "adaptation needs," that is, the set of adaptation actions that would be required to avoid any negative effect (and capture all positive effects) from climate change. It can be reduced by climate change mitigation, that is, by limiting the magnitude of climate change. The second circle represents the subset of adaptation actions that are possible considering technical and physical limits. Improving what can be done, for instance, through research and development, can expand this circle. The area between the first and second circles is the area of "unavoidable impacts" that one cannot adapt to (for instance, it is impossible to restore outdoor comfort under high temperature). The third circle represents the subset of adaptation actions that are desirable considering limited resources and competing priorities: some adaptation actions will be technically possible, but undesirable because they are too expensive and there are better alternative ways of improving welfare (e.g., investing in health or education). This circle can be expanded through economic growth, which increases resources that can be dedicated to adaptation. Finally, the last circle represents what will be done, taking into account the fact that market failures or practical, political, or institutional constraints will make it impossible to implement some desirable actions (see Chapter 15 and Section 17.3). The area between the first and the last circles represents residual impacts (i.e., the impacts that will remain after adaptation, because adapting to them is impossible, too expensive, or impossible owing to some barriers).

This discussion has consequences for timing of adaptation financing, given continuous changes in climate over time and uncertainties in the resulting impacts. Mathew et al. (2012) recommend the use of soft, short-term and reversible adaptation options with co-benefits for local governments. Giordano (2012) recommends the use of adaptive policies for modifying infrastructure, which can be robust across a wide range of plausible futures under climate change. Hochrainer and Mechler (2011) suggest that tools such as risk pooling may be more cost effective than risk reduction through engineering methods for low-frequency but high-impact hazards.

Financing adaptation programs is further discussed in the literature through the lens of distribution of costs. Stern (2006) argues climate change is characterized by a "double inequity," with those countries that are most vulnerable having generally contributed least (on a per capita basis) to the climate change drivers (Panayotou et al., 2002; Tol et al., 2004; Mendelsohn et al., 2006; Patz et al., 2007; SEGCC, 2007; Srinivasan et al., 2008; Füssel, 2010).

Distribution of responsibilities for financing adaptation has been the subject of lively debate. Füssel et al. (2012) note that answering the following questions can inform the debate on such burden sharing issues:

- Who pays for adaptation and how much should they contribute into the adaptation fund, and what criteria are appropriate in determining this?
- Who is eligible for receiving payments from the fund, and which criteria could be used for prioritizing recipients and for allocating funds?
- Which adaptation measures are eligible for funding, and what are the conditions and modalities for payment?
- How and by whom are such decisions made?

As of now no definitive conclusions have been reached. Table 17-1 sets out different approaches to defining eligibility for receiving adaptation funds.

17.2.6. Adaptation Benefits and Costs, Residual Damage, and Projects

Adaptation benefits are the reduction in damages plus any gains in climate-related welfare that occur following an adaptation action (National Research Council, 2010; World Bank, 2010a). Simplistically described, the cost of adaptation is the cost of any additional investment needed to adapt to or exploit future climate change (UNFCCC, 2007). But a full accounting needs to consider the resources spent to develop,

Table 17-1 | Four definitions of eligible adaptation.

Motivation for action	Relevant climatic factors	
	Observed and/or projected climate change	Climate change as well as natural climate variability
Climate is the main reason	*Definition 1*: Action occurs mainly to reduce the risks of observed or projected climate change. *Example*: Raising of existing dykes.	*Definition 2*: Action occurs mainly to reduce risks of climate change and climate variability. *Example*: Building of new dykes in areas that are currently unprotected.
Climate is one of several reasons	*Definition 3*: Actions that reduce the risks of observed or projected climate change even if they are also justified in the absence of climate change. *Example*: Economic diversification in predominantly agricultural regions.	*Definition 4*: Actions that reduce the risks of climate change and climate variability even if they are also justified in the absence of climate change. *Example*: Improved public health services.

Source: Füssel et al. (2012), adapted from Hallegatte (2008).

implement, and maintain the adaptation action along with accruing reduced damages or welfare increases involving monetary and non-monetary metrics.

Figure 17-2 provides a graphical representation of the link between the cost of adaptation (on the x-axis) and the residual cost of climate change (on the y-axis). A fraction of climate change damage can be reduced at no cost (e.g., by changing sowing dates in the agricultural sector). With increasing adaptation cost, climate change costs can be reduced further. In some cases (left-hand panel), sufficiently high adaptation spending can take residual cost to zero. In other cases (right-hand panel), some residual cost of climate change is unavoidable. Economics tells that the optimal level of adaptation equalizes the marginal adaptation cost and the marginal adaptation benefit, given by the point on the adaptation curves where the slope is –45°. If barriers and constraints (see Section 17.3) impose a suboptimal situation, the marginal costs and benefits of adaptation are not equal, possibly because there is too much investment in adaptation, so that investing $1 in adaptation reduces climate change residual cost by less than $1, or because there is not enough investment in adaptation and investing $1 more in adaptation would reduce residual cost by more than $1 (the situation in the right-hand panel).

Defining the costs and benefits of an "adaptation project" raises conceptual issues. Many actions have an influence on the impact of climate change without being adaptation projects per se (e.g., enhanced building norms). Many "adaptation projects" have consequences beyond a reduction in climate change impacts or an increase in welfare from exploiting opportunities (as discussed in the ancillary impacts section). Defining the adaptation component requires the definition of a baseline (What would be the impact of climate change in the absence of the adaptation action? What alternative projects would be implemented in the absence of climate change?), and the definition of "additionality"—the amount of additional loss reduction or welfare gain that happens because of the project. For instance, the building of new infrastructure may be marginally more costly because of adaptation to climate change but would still be undertaken without climate change and thus only a fraction of that cost and the resultant benefits would be labeled as occurring because of adaptation (see Dessai and Hulme, 2007).

In the climate change context, residual damages are those damages that remain after adaptation actions are taken. De Bruin et al. (2009b) and Hof et al. (2009) have examined the relationship between increasing adaptation effort and diminished residual damages.

17.2.7. A Broader Setting for Adaptation

Adaptation can be complementary to mitigation and to non-climate policies. An important concern is determining the balance between spending on adaptation versus that on other investments—mitigation and non-climate endeavors. Economics indicates the marginal social returns to all forms of expenditure should be the same, allowing for distributional impacts which can be done by differential weightings of benefits and costs to alternative income groups (Musgrave and Musgrave, 1973; Brent, 1996).

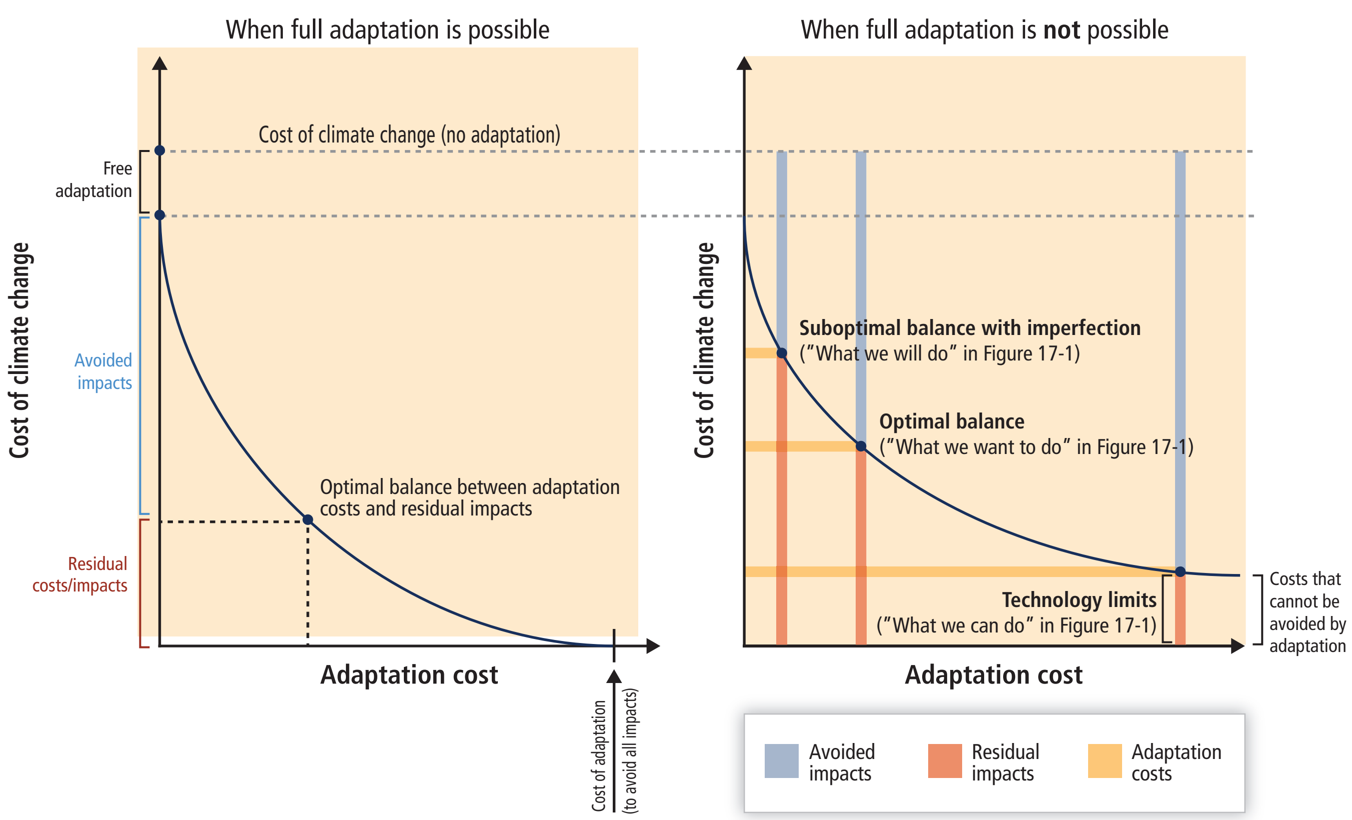

Figure 17-2 | Graphical representation of link between the cost of adaptation (on the x-axis) and the residual cost of climate change (on the y-axis). The left panel represents a case where full adaptation is possible, while the right panel represents a case in which there are unavoidable residual costs.

17.2.7.1. Adaptation and Mitigation as Competitive or Complementary Investments

Adaptation and mitigation funding require coordination as they are competing uses for scarce resources (WGII AR4 Chapter 18; Gawel et al., 2012). They also compete with consumption and non-climate investments. For example, some adaptation strategies use land (a shift from crops to livestock), as does mitigation via afforestation or biofuels, and all three would reduce ongoing crop production. Nevertheless, considering both adaptation and mitigation widens the set of actions and lowers the total cost of climate change (de Bruin et al., 2009a; Koetse and Rietveld, 2012; Wang and McCarl, 2013).

17.2.7.2. Adaptation and Development

There is a relationship between adaptation and socioeconomic development, particularly in lower income countries (as extensively discussed in Chapters 10, 13, and 20). In terms of complementarity between the two, studies show that both development and adaptation can be enhanced via climate-resilient road development (World Bank, 2009); installation of agricultural investments that enhance income, heat tolerance, and drought resilience (Butt et al., 2006;Ringer et al., 2008); or improvements in public health infrastructure that increase capability to deal with climate-enhanced disease and other diseases (Markandya and Chiabai, 2009; Samet, 2010). In addition, development in general can increase adaptive capacity through enhancements in human and other capital (Schelling, 1992, 1997; Tol, 2005; IPCC, 2012). Finally, adaptation efforts may reduce adaptation deficits regarding vulnerability to existing climate and enhance general development (Burton, 2004). Thus, development goals can be generally consistent with adaptation goals, with one possibly being an ancillary effect of the other, although this is not always the case. For example, Hansone et al. (2001) find that urbanization of flood-prone areas increases vulnerability and adaptation needs while Burby et al. (2001) and Hallegatte (2012) indicate better protection may trigger additional development in at-risk areas and create increased vulnerability to extreme events.

17.3. Decision Making and Economic Context for Adaptation

Adaptation will be carried out by multiple public and private actors who face a number of decision-making barriers that may limit adaptation. Chapter 16 and many papers (e.g., Fankhauser et al., 1999; Cimato and Mullan, 2010; Moser and Eckstrom 2010; Biesbroek et al., 2011; Fankhauser and Soare, 2013) investigate these barriers. This section

Frequently Asked Questions

FAQ 17.1 | Given the significant uncertainty about the effects of adaptation measures, can economics contribute much to decision making in this area?

Economic methods have been developed to inform a wide range of issues that involve decision making in the face of uncertainty. Indeed some of these methods have already been applied to the evaluation of adaptation measures, such as decisions on which coastal areas to protect and how much to protect them.

A range of methods can be applied, depending on the available information and the questions being asked. Where probabilities can be attached to different outcomes that may result from an adaptation measure, economic tools such as risk and portfolio theory allow us to choose the adaptation option that maximizes the expected net benefits, while allowing for the risks associated with different options. Such an approach compares not only the net benefits of each measure but also the risks associated with it (e.g., the possibility of a very poor outcome).

In situations where probabilities cannot be defined, economic analysis can define scenarios that describe a possible set of outcomes for each adaptation measure that meet some criteria of minimum acceptable benefits across a range of scenarios, allowing the decision maker to explore different levels of acceptable benefits in a systematic way. That, of course, hinges on the definition of "acceptability," which is a complex matter that accounts for community values as well as physical outcomes. These approaches can be applied to climate change impacts such as sea level rise, river flooding, and energy planning.

In some cases it is difficult to place specific economic values on important outcomes (e.g., disasters involving large-scale loss of life). An alternative to the risk or portfolio theory approach can then be used, that identifies the least-cost solution that keeps probable losses to an acceptable level.

There are, however, still unanswered questions on how to apply economic methods to this kind of problem (particularly when the changes caused by climate change are large and when people's valuations may be changed), and on how to improve the quality of information on the possible impacts and benefits.

reviews them from an economic perspective, and then turns to the decision-making frameworks that can help implement adaptation actions in spite of these barriers.

17.3.1. Economic Barriers to Adaptation Decision Making

17.3.1.1. Transaction Costs, Information, and Adjustment Costs

Transaction costs include the costs of accessing markets and information, along with reaching an agreement and enforcement costs (Coase, 1937, 1960; Williamson, 1979). Because of transaction costs, a beneficial adaptation action may be undesirable. Two specific types of transaction costs are those relating to information and those relating to adjustment.

Information acquisition costs can represent a significant obstacle, for instance, when climate and weather data are costly or difficult to access (e.g., Cimato and Mullan, 2010; Ford et al., 2011; Scott et al., 2011). Because information is a public good, private actors tend to under-provide it and there is a role for government and public authorities to support its production and dissemination (e.g., through research funding, observation networks, or information distribution systems; Fankhauser et al., 1999; Mendelsohn, 2000; Trenberth, 2008).

Adjustment costs represent another barrier, especially in the presence of uncertainty and learning, and when long-lived capital is concerned. Fankhauser et al. (1999) discuss adjustment costs as a barrier to early capital replacement to adapt to a different climate. Kelly and Kolstad (2005) define adjustment costs as the cost incurred while learning about new climate conditions. Using these different definitions, these analyses suggest that adjustment costs can represent a significant share of adaptation costs.

17.3.1.2. Market Failures and Missing Markets

Adaptation may also face market failures such as externalities, information asymmetry, and moral hazards (see Section 17.2.1; Osberghaus et al., 2010a). As a consequence, some socially desirable actions may not be privately profitable. For example, flood mitigation measures may not be implemented in spite of their benefits, when flood risks are partly assumed by insurance or post-disaster support, transferring risk to the community (a case of moral hazard; Burby et al., 1991; Laffont, 1995). There are also externalities, as adaptation actions by one household, firm, or even country may create higher damages for others. This is the case with transboundary waters, when increased irrigation in one country creates water scarcity downstream (Goulden et al., 2009). Trans-sector effects can also take place, for instance when adaptation in one sector creates needs in another sector (e.g., the impact on transportation of agriculture adaptation; see Attavanich et al., 2013). Incentives for private adaptation actions may also be lacking for public goods and common resources without property rights (e.g., biodiversity and natural areas, tradition, and culture). And adaptation may exhibit increasing returns or large fixed costs, leading to insufficient adaptation investments (e.g., Eisenack, 2013). In such contexts, public norms and standards, direct public investment, tax measures, or national or international institutions for adaptation coordination are needed to avoid maladaptation.

17.3.1.3. Behavioral Obstacles to Adaptation

Economic agents adapt continuously to climate conditions, though not always using the available information, especially long-term projections of consequences (Camerer and Kunreuther, 1989; Thaler, 1999; Michel-Kerjan, 2006). Individuals often defer choosing between ambiguous choices (Tversky and Shafir, 1992; Trope and Lieberman, 2003) and make decisions that are time inconsistent (e.g., they attribute a lower weight to the long term through "hyperbolic discounting"; see Ainslie, 1975). They also systematically favor the status quo and familiar choices (Johnson and Goldstein, 2003). Also, individuals value profits and losses differently (Tversky and Kahnman, 1974). Behavioral issues may lead to suboptimal adaptation decisions, as illustrated with case studies in Germany and Zimbabwe in Grothmann and Patt (2005). Particularly important is the fact that the provision of climate information needs to account for cognitive failures (Suarez and Patt, 2004; Osberghaus et al., 2010b). Individual behavioral barriers extend to cultural factors and social norms, which can support or impair adaptation as illustrated by Nielsen and Reenberg (2010) in Burkina Faso.

17.3.1.4. Ethics and Distributional Issues

A difficulty in allocating adaptation resources noted in Section 17.2.3 is the limitation of indicators based on costs and benefits (Adger et al., 2005; Füssel, 2010). Outcomes are often measured using such methods but their limits are well known, (e.g., CMEPSP, 2009; OECD, 2009; Heal, 2012) and include the failure to take into account resource depletion, environmental change, and distributional issues.

Distributional issues may justify public intervention based on ethics and values. Climate change impacts vary greatly by social group, and many have suggested that the poor are particularly vulnerable (e.g., Stern, 2006; Füssel et al., 2012). Some individuals, firms, communities, and even countries may be unable to afford adaptation, even if it is in their own interest. Also, individuals with different world views or preferences (e.g., regarding risk aversion; see Adger et al., 2009) may ask for different adaptation measures and have different views of what is an acceptable level of residual risk (Peters and Slovic, 1996). Consideration of justice and fairness will play a role in adaptation option design (Adger et al., 2006; Brauch, 2009a,b; Dalby, 2009; O'Brien et al., 2009, 2010; Pelling and Dill, 2009). The implementation of adaptation options may thus require taking into account the political economy of reforms and the need to compensate losers (World Bank, 2012).

The traditional economic approach suggests choosing the most cost-effective projects and then resorting to financial transfers to satisfy equity objectives (Atkinson and Stiglitz, 1976; Brown and Heal, 1979). However, this embodies strong assumptions including the ability to realize perfect and costless financial transfers. In more realistic situations the choice is not so clear cut. In practical terms, transfers are difficult to organize and may not be politically acceptable (Kanbur, 2010).

In these cases, adaptation decision making needs to account for both the net benefits and the impacts on equity (Aakre and Rübbelke, 2010).

17.3.1.5 Coordination, Government Failures, and Political Economy

One of the main roles of governments and local authorities is to remove barriers—realigning the incentives of individuals with the goals of society, providing the public goods needed for adaptation, or helping with behavioral and cognitive biases. But governments and local authorities face their own barriers, often referred to as government or regulatory failures (Krueger, 1990). First, government and local authority decision makers, as individuals, face their own barriers, such a cognitive and behavioral biases (Podsakoff et al., 1990). Public decision makers are also confronted with moral hazard, for instance, when subnational entities are provided support from the government in case of disaster (Michel-Kerjan, 2006). Second, governments may have access to insufficient resources or limited adaptation capacity, especially in poorer countries and where governments have limited access to capital markets and are unable to fund projects, even when they are cost efficient (e.g., Brooks et al., 2005; Smit and Wandel, 2006; World Bank, 2012). There can also be coordination failures within the government, as many adaptation options require multi-ministry actions (e.g., the reduction of flood risks may require some prevention measure implemented by the environmental ministry and an insurance scheme regulated by the ministry of finance; World Bank, 2013).

Other government failures can arise. Frequently government action is driven by narrow interest groups and is not in the public interest (Levine and Forrence, 1990; James, 2000). Multi-stakeholder approaches have been shown to help address these problems, with a relevant example for this context being coral reef management in Tobago (Adger et al., 2005).

17.3.1.6. Uncertainty

Decisions about adaptation have to be made in the face of uncertainty on items ranging from demography and technology to economic futures. Climate change adds additional sources of uncertainty, including uncertainty about the extent and patterns of future climate change (see the WGI contribution to the AR5), which is dependent on uncertain socioeconomic development pathways and climate policies (see the WGIII contribution to the AR5), and uncertainty about the reaction and adaptation of ecosystems (see Chapters 3 to 13).

Patt and Schröter (2008) show in a case study in Mozambique that major uncertainties are a strong barrier to successful adaptation. Uncertainty, coupled with the long lifespan of a number of options, can lead to "maladaptation," that is, an adaptation action that leads to increased vulnerability. An "*avoidable*" maladaptation arises from a poor *ex ante choice*, where available information is not used properly. An "*unavoidable*" *ex post* maladaptation can result from entirely appropriate decisions based on the information that was the best available *at the time of decision making*, but subsequently proves to have been wrong. An example of the latter is a precautionary restriction prohibiting new construction in areas potentially at risk of sea level rise. Applying such a precautionary approach makes sense when (1) decisions are at least partly irreversible (e.g., building in flood-prone areas cannot easily be "un-built") and (2) the cost of a worst-case scenario is very high. Such a precautionary measure can make economic sense *ex ante*, even if sea level rise eventually remains in the lower range of possible outcomes, making the construction restriction unnecessary.

17.3.2. Economic Decision Making with Uncertainty

Decision making under uncertainty is a central question for climate change policy and is discussed in many chapters of the AR5, especially in Chapter 2 and WGIII AR5 Chapters 2 and 3. This section focuses on the economic approaches to decision making under uncertainty, including decision-making techniques, valuation tools, and multi-metric decision making.

17.3.2.1. Cost-Benefit Analysis and Related Methods

There are different tools for decision making that can be applied in different contexts and with different information. Cost-benefit analysis under uncertainty applied to adaptation uses subjective probabilities for different climate futures (e.g., Tebaldi et al., 2005; New and Hulme, 2006; see also Chapter 2). The "best" project is the one that maximizes the expected net present value of costs and benefits. Risk aversion can be taken into account through (nonlinear) welfare functions or the explicit introduction of a risk premium.

When conducting cost-benefit analyses under uncertainty, an important question is the timing of action, that is, the possibility of delaying a decision until more information is available (e.g., Fankhauser and Soare, 2013). Real option techniques are an extension of cost-benefit analysis to capture this possibility and balance the costs and benefits of delaying a decision (Arrow and Fisher, 1974; Henry, 1974). The benefits depend on how much learning can take place over time. A key issue concerns irreversible actions, such as the destruction of a unique environment (Heal and Kristrom, 2003).

Application of cost-benefit or real option analysis requires evaluations in monetary terms. For market impacts, prices may need to be corrected for policies, monopoly power, or other external factors distorting market prices (Squire and van der Tak, 1975). But a cost-benefit analysis also often requires the valuation of non-market costs and benefits. This is the case for impacts on public health, cultural heritage, environmental quality and ecosystems, and distributional impacts. Valuation of non-market impact is difficult because of values and preferences heterogeneity, and subject to controversies—for example, on the value to attribute to avoided death (see Viscusi and Aldy, 2003).

There has been progress in valuation of ecosystem services, as elaborated in the Millennium Ecosystem Assessment (MEA, 2005), The Economics of Ecosystems and Biodiversity (TEEB, 2010), and Bateman et al. (2011). Two main categories of approaches have been developed: revealed and stated preference methods. The latter is based on what people say about their preferences, while the former uses their actual decisions (e.g., how much they pay for a house) and is often considered more accurate. Other approaches include avoided or replacement cost, that is, measuring the cost of providing the ecosystem service artificially. When local information is not available, value transfer techniques can be applied moving information from other locations. For example, Brander et al. (2012) applies value transfer to climate change impacts on wetlands but caution is required in making such transfers (National Research Council, 2005; Navrud and Ready, 2007).

Theoretically, cost-benefit approaches can account for distributional impacts, for instance, through attribution of a higher weight to the poorest (Harberger, 1984). Results are however highly dependent on preferences that can be extremely heterogeneous and difficult to measure (Barsky et al., 1997). As discussed in detail in Chapter 2, valuation and decision making cannot be separated from the institutional and social contexts (e.g., what is considered as a right). Yet, overall, as concluded by the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX), the applicability of rigorous community-based adaptations (CBAs) for evaluations of adaptation to climate variability and change may be limited (Handmer et al., 2012).

17.3.2.2. Multi-Metric Decision Making for Adaptation

Multi-metric decision making provides a broader framework, which also permits balancing among multiple, potentially competing objectives (Keeney and Raiffa, 1993). This branch of decision analysis is also known as multi-criterion analysis. Such an approach is helpful when decision makers have difficulty in trading off different objectives (Martinez-Alier et al., 1998). Using multiple criteria, decision makers can include a full range of social, environmental, technical, and economic criteria—mainly by quantifying and displaying trade-offs. Multi-criterion analyses have been applied to adaptation issues including urban flood risk (Kubal et al., 2009; Grafakos, 2012; Viguie and Hallegatte, 2012), agricultural vulnerability (Julius and Scheraga, 2000), and choice of adaptation options in the Netherlands (Brouwer and van Ek, 2004; de Bruin et al., 2009a), Canada (Qin et al., 2008), and Africa (Smith and Lenhart, 1996). The United Nations Framework Convention on Climate Change (UNFCCC) developed guidelines for the adaptation assessment process in developing countries in which it suggests the use of multi-criteria analysis (UNFCCC, 2002). As an illustration, Figure 17-3 shows a multi-criteria analysis of three urban policies in the Paris agglomeration, using five policy objectives and success indicators (climate change mitigation, adaptation and risk management, natural area and biodiversity protection, housing affordability, and policy neutrality).

17.3.2.3. Non-Probabilistic Methodologies

Cost-benefit analysis and related methods require probabilities for each climate scenario. But in most cases, it may be impossible to define (or to agree on) probabilities for alternative outcomes, or even to identify the set of possible futures (including highly improbable events) (Henry and Henry, 2002; Gilboa, 2010; Millner et al., 2010; Kunreuther et al., 2012). This is especially true for low-probability, high-impact cases or poorly understood risks (Weitzman, 2009; Kunreuther et al., 2012). In

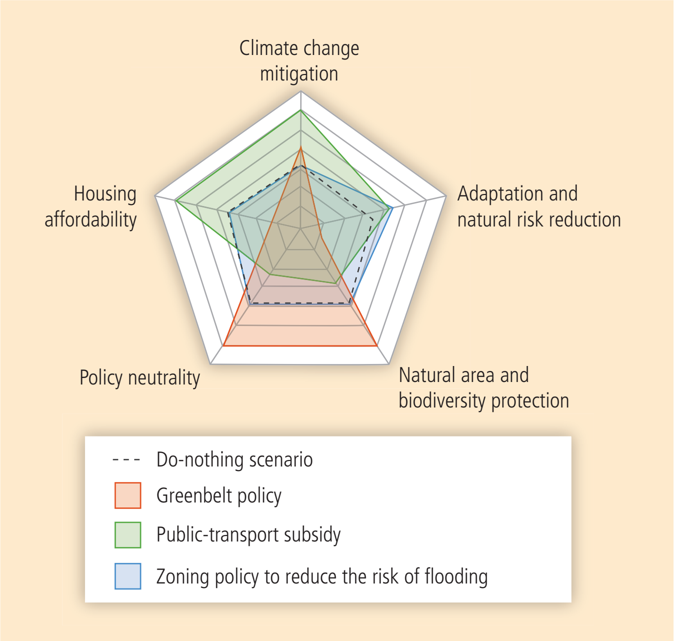

Figure 17-3 | Consequences of three policies in the Paris agglomeration: a greenbelt policy, a public transport subsidy, and a zoning policy to reduce the risk of flooding, measured using five different metrics representing five policy objectives. Axes orientation is such that directions toward the exterior of the radar plot represent positive outcomes (Viguié and Hallegatte, 2012).

such contexts, various approaches have been proposed (see reviews in Ranger et al., 2010; Hallegatte et al., 2012; see also Chapter 2).

Scenario-based analyses study different policies in different scenarios that try and cover the uncertainty space for key parameters (Schwartz, 1996). This is the approach followed by many climate change impact and adaptation studies when using several IPCC *Special Report on Emission Scenarios* (SRES) scenarios (Carter et al., 2001, 2007; Hallegatte et al., 2011). Then, various methodologies or criteria can be used to make a decision.

The *maxi–min* criterion suggests choosing the decision with the best worst-case outcome and the *mini–max regret* criterion (Savage, 1951) suggests choosing the decision with the smallest deviation from optimality in any state of the world. Proposals for "no regrets" adaptation decisions (Callaway and Hellmuth, 2007; Heltberg et al., 2009) employ such criteria. Hybrid criteria balance between optimal and worst case performance (Hurwicz, 1951; Aaheim and Bretteville, 2001; Froyn, 2005).

Another criterion is based on "robustness" and seeks decisions that will perform well over a wide range of plausible climate futures, socioeconomic trends, and other factors (Lempert and Schlesinger, 2000; Lempert et al., 2006; Dessai and Hulme, 2007; Lempert and Collins, 2007; Groves et al., 2008; Wilby and Dessai, 2010; WUCA, 2010; Brown et al., 2011; Lempert and Kalra, 2011). Instead of starting from a few scenarios, these methods start with an option or a project and test it under a large number of scenarios to identify its vulnerabilities to uncertain parameters. Small adjustment or large changes in options or projects can then be identified to minimize these vulnerabilities. Example implementations include InfoGap, which has been used to inform adaptation decisions in water management (Ben-Haim, 2001; Korteling et al., 2013); RDM (robust decision making), which has been used for water management and flood risk management planning (Lempert et al., 2003; Lempert and Groves, 2010; Lempert and Kalra, 2011; Matrosov et al., 2013); and robust control optimization (Hansen and Sargent, 2008).

Figure 17-4 illustrates the application of robust decision making on flood risks in Ho Chi Minh City (Lempert et al., 2013). The analysis examined different risk management portfolios (including, for instance, raising homes and retreat). Each portfolio was simulated in 1000 scenarios, covering socioeconomic and climate uncertainty. The RDM analysis found that the current plan is robust to a wide range of possible future population and economic trends. But it would keep risk below current levels only if rainfall intensities increase by no more than 5% and if the Saigon River rises less than 45 cm. Additional measures were found that made the situation robust for increases in rainfall intensity of up to 35% and increases in the level of the Saigon River of up to 100 cm.

17.4. Costing Adaptation

Interest in estimating the costs of adaptation has grown as the need for action has become clearer. The literature focuses on two levels of costing: global scale estimates, largely to assess the overall need for adaptation finance funds; and regional and local-scale estimates, often limited to a particular vulnerable economic sector, which may be applied to inform budgeting or to support adaptation decision making, or to allocate scarce resources among the best prospects for effective adaptation. The methods for these two types of studies vary widely, but for the important methodological considerations for costing adaptation are similar for both types.

17.4.1. Methodological Considerations

17.4.1.1. Data Quality and Quantity

There is very little discussion of data gaps related to assessing the benefits of adaptation, but poor or sparse data obviously limit the accuracy of these estimates. Callaway (2004) suggests that a major challenge is the low quality and limited nature of data, especially in many developing countries, and notes many transactions are not reported because they occur in informal economies and social networks. In a more general setting Hughes et al. (2010) note that historical weather data are not typically sufficiently detailed while others note sparse data on costs of adaptation actions. For example, Bjarnadottie et al. (2011) note incomplete and contradictory data on house retrofit costs for hurricane protection. Also there are simply missing non-market data on such items as the value of ecosystem services (Agrawala and Fankhauser, 2008), particularly as affected by climate and possible adaptation.

17.4.1.2. Costs and Benefits Are Location-Specific

Calculating localized impacts requires detailed geographical knowledge of climate change impacts, but these are a major source of uncertainty

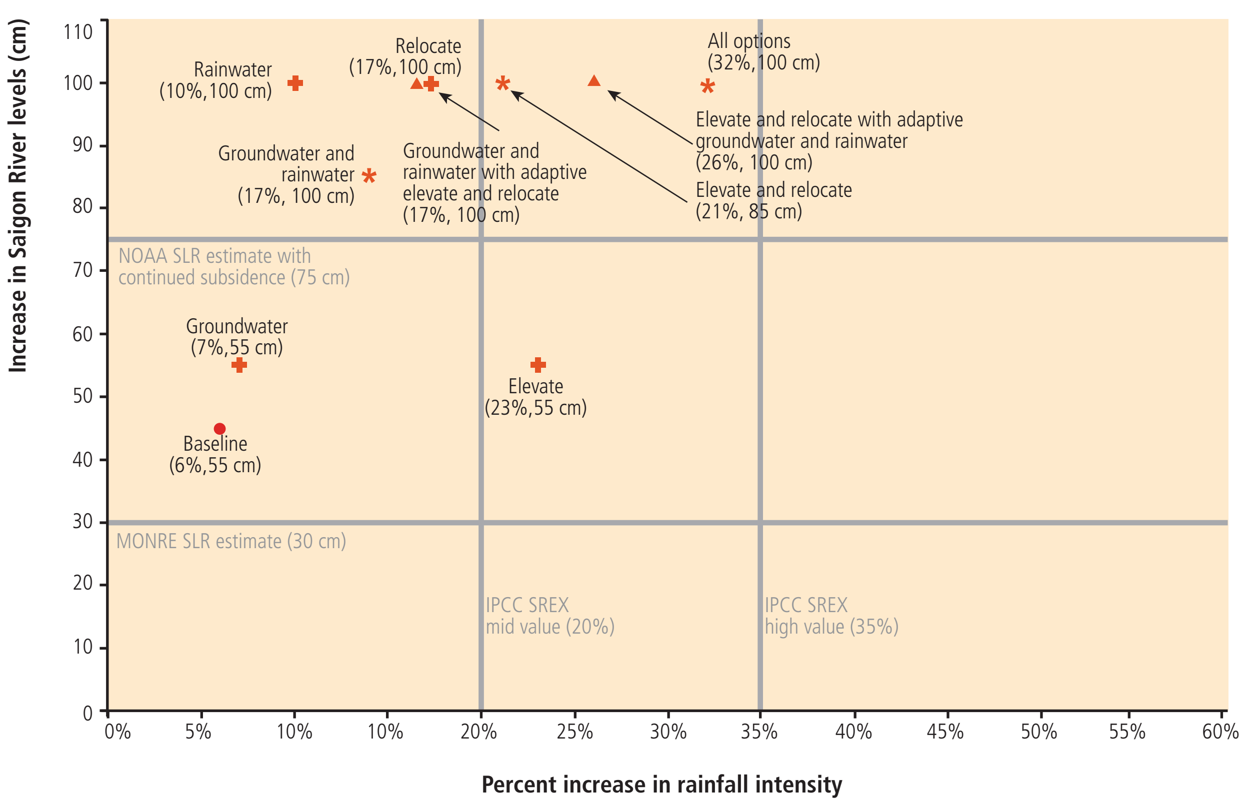

Figure 17-4 | Various risk management strategies in Ho Chi Minh City, and their robustness to increases in river levels and rainfall intensity. Different options can cope with different amplitudes of environmental change (Lempert et al., 2013).

in climate models (see Refsgaard et al., 2013). Global estimates of adaptation cost are generally not grounded in local-scale physical attributes important for adaptation, which in part explains why local and regional-scale adaptation cost estimates are not consistent with global estimates (Agrawala and Fankhauser, 2008). Compared with developed countries, there is also a limited understanding of the potential market sector impacts of climate change in developing countries.

17.4.1.3. Costs and Benefits Depend on Socioeconomics

It is sometimes assumed that climate will change but society will not (Pielke, 2007; Hallegatte et al., 2011; Mechler and Bouwer, 2013). Future development paths affect climate change impact estimates, and can alter estimates from positive to negative impacts or vice versa. Some studies show higher growth rates raise hurricane vulnerability (Bjarnadottir, 2011). On the other hand, higher incomes allow the funding of risk-reducing policies.

17.4.1.4. Discount Rates Matter

Because adaptation costs and consequences occur over time, discount rates are a core question. Opinions vary sharply on this question (Baum, 2009; Heal 2009). Hof et al. (2010) notes that a low discount rate is needed for distant future climate change to matter. A low discount rate is the primary reason for the relatively high estimates of climate damage in the Stern Review (Stern, 2006). For climate adaptation projects, the social or consumption discount rate is the relevant one (Heal, 2009). The rates used fall between 0.1 and 2.5%, although without good arguments for specific values (see Heal, 2009). Nordhaus (2008) chooses a value of 1.5% while Stern uses a much lower value of 0.1%. Nordhaus emphasizes consistency with the rate of return on investment as a driving rationale while Stern points to ethical issues. Allowing environmental services to enter consumption can change the social discount rate substantially and generate a low or even negative social discount rate (Guesnerie, 2004; Sterner and Persson, 2007; Heal, 2009). The UK Treasury now mandates the use of declining discount rates for long-term projects, as suggested by behavioral studies and by theoretical analysis (Arrow et al., 2012).

17.4.2. Review of Existing Global Estimates: Gaps and Limitations

There has been a limited number of global and regional adaptation cost assessments over the last few years (Stern, 2006; World Bank, 2006, 2010a; Oxfam, 2007; UNDP, 2007; UNFCCC, 2007, 2008). These estimates exhibit a large range and have been completed mostly for developing countries. The most recent and most comprehensive to date global adaptation costs range from US$70 to more than US$100 billion annually by 2050 (World Bank, 2010a; see Table 17-2).

IPCC (2012) considers confidence in these numbers to be low because the estimates are derived from only three relatively independent lines of evidence. World Bank (2006) estimates the cost of climate proofing foreign direct investments (FDI), gross domestic investments (GDI), and Official Development Assistance (ODA), as does the Stern Review (2006), Oxfam (2007), and UNDP (2007). UNFCCC (2007) calculated existing and planned investment and financial flows (I&FF), and then estimated the additional investment required for adaptation as a premium on existing and planned investments. The World Bank (2010a) followed the UNFCCC (2007) methodology of estimating the premium climate change imposes on a baseline of existing and planned investment, but included more extensive modeling (as opposed to developing unit cost estimates), constructed marginal cost curves and climate stressor-response functions for adaptation actions, and included maintenance and coastal port upgrading costs.

Given their common approaches these estimates are interlinked, which explains the seeming convergence of their estimates in later years, as discussed by Parry et al. (2009). However, there are important differences in terms of sectoral estimates, as Figure 17-5 shows in comparing the UNFCCC (2007) and World Bank (2010a) studies. Extreme events, a potential source of large adaptation costs, are not properly covered, and these studies take into account a limited set of adaptation options. In addition, the World Bank (2010a) estimates report higher ranges of estimates, reflecting additional effort to account for uncertainty. Parry et al. (2009) consider the UNFCCC (2007) estimates a significant underestimation by at least a factor of two to three plus omitted costs in ecosystem services, energy, manufacturing, retailing, and tourism. Thus the numbers have to be treated with caution. There are a number

Table 17-2 | Estimates of global costs of adaptation.

Study	Results (billion US$ per year)	Time frame	Sectors	Methodology and comments
World Bank (2006)	9–41	Present	Unspecified	Cost of climate proofing foreign direct investments, gross domestic investments, and Official Development Assistance
Stern (2007)	4–37	Present	Unspecified	Update of World Bank (2006)
Oxfam (2007)	>50	Present	Unspecified	World Bank (2006) plus extrapolation of cost estimates from national adaptation plans and NGO projects
UNDP (2007)	86–109	2015	Unspecified	World Bank (2006) plus costing of targets for adapting poverty reduction programs and strengthening disaster response systems
UNFCCC (2007)	28–67	2030	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure	Planned investment and financial flows required for the international community
World Bank (2010a)	70–100	2050	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure; extreme events	Improvement on UNFCCC (2007): more precise unit cost, inclusion of cost of maintenance and port upgrading, risks from sea level rise and storm surges

Source: Modified from Agrawala and Fankhauser (2008) and Parry et al. (2009) to include estimates from World Bank (2010a).

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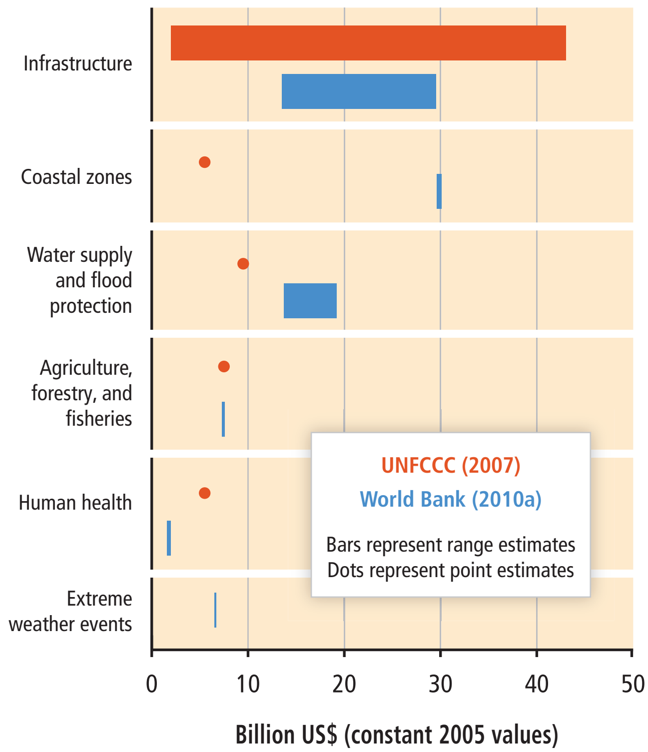

Figure 17-5 | Comparison of sectoral results on the costs of adaptation in developing countries across the UNFCCC and World Bank studies. Note: Bars indicate estimates using ranges; points indicate point estimates.

of gaps, challenges, and omissions associated with those global estimates that merit further discussion.

The practical challenges of conducting global adaptation cost studies are apparent in the literature (as assessed in Parry et al., 2009; World Bank, 2010a; IPCC, 2012). The broad scope of these studies limits the analysis to few climate scenarios, and while the scenarios might be strategically chosen it is difficult to represent fully the range of future adaptation costs across all sectors. The broad scope also limits comprehensive consideration of adaptation options, non-market and co-benefits, equity issues, and adaptation decision making (such limitations also apply to local and regional scale studies; see Section 17.4.3). The global studies, designed to reflect the best available methods and data for the purpose of estimating the magnitude of the global economic adaptation challenge, achieve this limited goal but must be interpreted in light of these important limitations and uncertainties.

17.4.3. Consistency between Localized and Global Analyses

Adaptation costs and benefits are derived to guide specific investment decisions, generally at national and local levels, or to derive a "price tag" for overall funding needs for adaptation (generally at a global level). Given these different purposes it is difficult to compare "local," that is, national and sectoral, with global numbers. The quantity/quality of local studies also varies by sector with more treatment of adaptation in coastal zones and agriculture (Agrawala and Fankhauser, 2008; see Table 17-3). Less is known and many gaps remain for sectors such as water resources, energy, ecosystems, infrastructure, tourism, and public health. Also assessments have predominantly been conducted in a developed country context (see Table 17-1 for examples of costs and benefits assessment).

However, as Fankhauser (2010) notes, with the sole exception of coastal protection costs, adaptation costs have shown little convergence locally or in terms of sectoral to global costs. The World Bank (2010a) study uniquely takes a two-track approach doing parallel national (seven cases) and global adaptation estimates. For a number of country studies (Bangladesh, Samoa, and Vietnam) a cross-country comparison of local and global adaptation costs was made, with the costs in terms of gross domestic product (GDP) found to be in reasonable agreement. Costs for strengthening infrastructure against windstorms, precipitation, and flooding were about 10 to 20% higher compared to disaggregated global estimates, largely owing to the ability of country-level studies to consider at least some socially contingent impacts (World Bank, 2010a,b,c,d). Further, there is evidence of under-investment in adaptation (UNDP, 2007), with global estimates of the need for adaptation funds variously estimated in the range of US$70 to US$100 billion annually (World Bank, 2010a), but with actual expenditures in 2011 estimated at US$244 million (Elbehri et al, 2011), and in 2012 estimated at US$395 million (Schalatek et al., 2012).

17.4.4. Selected Studies on Sectors or Regions

This section focuses on studies that illustrate current practice in estimating adaptation economics, with a particular focus on support of adaptation decision making through economic analysis. Within that class of work, there are two broad categories of economic analyses of adaptation at the sectoral level: econometric and simulation approaches.

Econometric studies generally examine the nature of observed adaptations or the estimation of climate change effects to which farmers have adapted. Such studies rely on observed cross-sectional, time series, or panel data. Examples include those where one implicitly assumes adaptation has occurred linking temperature and precipitation to land values and crop yields or land values (e.g., Mendelsohn et al., 1994; Schlenker et al., 2006) or those identifying adaptations in terms of altered decisions, for

Table 17-3 | Coverage of adaptation costs and benefits.

Sector	Analytical coverage	Cost estimates	Benefit estimates
Coastal zones	Comprehensive	✓✓✓	✓✓✓
Agriculture	Comprehensive	—	✓✓✓
Water	Isolated case studies	✓	✓
Energy	North America, Europe	✓✓	✓✓
Infrastructure	Cross-cutting, partly covered in other sectors	✓✓	—
Health	Selected impacts	✓	—
Tourism	Winter tourism	✓	—

Note: Three checks indicates good to excellent coverage of the topic in the literature; two checks indicates medium coverage; one check indicates limited coverage; the absence of a check indicates extremely limited or no coverage. Note that indicators reflect literature review through publication of source in 2008.

Source: Agrawala and Fankhauser (2008).

Frequently Asked Questions

FAQ 17.2 | Could economic approaches bias adaptation policy and decisions against the interests of the poor, vulnerable populations, or ecosystems?

A narrow economic approach can fail to account adequately for such items as ecosystem services and community value systems, which are sometimes not considered in economic analysis or undervalued by market prices, or for which data are insufficient. This can bias decisions against the poor, vulnerable populations, or the maintenance of important ecosystems. For example, the market value of timber neither reflects the ecological and hydrological functions of trees nor the forest products whose values arise from economic sectors outside the timber industry, like medicines. Furthermore, some communities value certain assets (historic buildings, religious sites) differently than others. Broader economic approaches, however, can attach monetary values to non-market impacts, referred to as externalities, placing an economic value on ecosystem services like breathable air, carbon capture and storage (in forests and oceans), and usable water. The values for these factors may be less certain than those attached to market impacts, which can be quantified with market data, but they are still useful to provide economic assessments that are less biased against ecosystems.

But economic analysis, which focuses on the monetary costs and benefits of an option, is just one important component of decision making relating to adaptation alternatives, and final decisions about such measures are almost never based on this information alone. Societal decision making also accounts for equity—who gains and who loses—and for the impacts of the measures on other factors that are not represented in monetary terms. In other words, communities make decisions in a larger context, taking into account other socioeconomic and political factors. What is crucial is that the overall decision framework is broad, with both economic and non-economic factors being taken into consideration.

A frequently used decision-making framework that provides for the inclusion of economic and non-economic indicators to measure the impacts of a policy, including impacts on vulnerable groups and ecosystems, is multi-criteria analysis (MCA). But as with all decision-making approaches, the challenge for MCA and methods like it is the subjective choices that have to be made about what weights to attach to all the relevant criteria that go into the analysis, including how the adaptation measure being studied impacts poor or vulnerable populations, or how fair it is in the distribution of who pays compared to who benefits.

example, Seo and Mendelsohn (2008a,c) look at enterprise choice, while Mu et al. (2013) look at stocking rate adjustments. Such approaches can also be used to estimate the marginal effect of adaptation, provided that "without adaptation" estimates can be developed (Mendelsohn and Dinar, 2003).

The simulation approach, by contrast, traces costs and benefits of adaptation strategies through mechanisms of interest, typically through a series of climate-biophysical-behavioral response-economic components. Within simulation modeling there are two main threads in the behavioral response-economic component of the simulation. The first involves rational actors who consider the benefit and cost consequences of their choices and pursue economically efficient adaptation outcomes, and the second involves a decision-rule or reference-based characterization of the response of actors to climate stressors (Schlenker et al., 2006; Dinar and Mendelsohn, 2011). As noted later, in many sectors the current practice begins with the simpler decision-rule based approach, and may progress to consider benefits and costs, and then perhaps to consider other factors, such as equity and non-market values.

The key advantages of an econometric approach are reliance on real-world data, the use of "natural experiments" in some cases, and an ability to reflect the joint costs and benefits of multiple adaptation strategies to the extent they are employed together in the real world (Mendelsohn and Neumann, 1999; Dinar and Mendelsohn, 2011). The econometric approach does not require the analyst to simulate all adaptation mechanisms, only to establish that there is a robust relationship between a climate stressor and the outcome of interest. The data required to implement the approach are limited, so the approach can be applied broadly. The key disadvantages of the econometric approach are an inability to trace transmission mechanisms of specific adaptation measures or to isolate the marginal effect of these strategies or measures; the inability to transfer estimates out of context (e.g., an African study does not apply to Asia, where the climate, adaptation, and social context all differ and affect the marginal costs and benefits of adaptation measures); and that the statistical estimation can be challenging and sometimes subject to multiple interpretations (Schlenker et al., 2005).

Simulation modeling can be demanding—a key disadvantage—as it requires extensive data inputs and careful calibration. Where data and models are available, however, the simulation modeling method works well. For example, an agricultural adaptation modeling system can estimate such factors as the incremental change in crop output and water

Table 17-4 | Studies illustrating economic evaluation of adaptation options.

Sector	Study and scope	Methodology	Key points illustrated
Agriculture, forestry, and livestock	Seo and coinvestigators (e.g., Seo et al., 2008b, 2009b, 2011): Impacts to livestock producers in Africa	Econometric. Examines the economic choices that livestock owners make to maintain production in the face of climate. Insights into adaption possibilities are achieved by examining the ways economic choices vary over locations and times with varying climate conditions.	• Consideration of multiple options (implicit) • Residual impacts reflected • Applicable at multiple geographic scales • Results provide a ready means to re-estimate results for multiple climate scenarios.
	Butt et al. (2006): Crop sector in Mali	Simulation. Simulates the economic implications of potential adaptation possibilities. Examines the consequences of migration in cropping patterns, development of heat resistant cultivars, reduction in soil productivity loss, cropland expansion, and changes in trade patterns.	• Broad consideration of options (explicit, allowing for ranking of measures) • Residual impacts reflected • Rigorous economic costing of adaptation options and consequences for yields, revenue, and food security
	Sutton et al. (2013): Crop and livestock sector in four eastern European and central Asian countries	Simulation with benefit/cost analysis. Ranks options initially based on net economic benefits over 2010–2050 period. Considers non-market and socially contingent effects through stakeholder consultation process.	• Broad consideration of options (explicit, measures ranked) • Very broad representation of climate scenarios (56 General Circulation Model–Special Report on Emission Scenarios combinations) • Rigorous economic costing of adaptation options • Integrated analysis of agriculture and irrigation water sectors
Sea level rise and coastal systems	Nichols and Tol (2006): Coastal regions at a global scale	Simulation of adaptation through construction of seawalls and levees, adoption of beach nourishment to maintain recreational value, and migration of coastal dwellers from vulnerable areas. The study reflects an economic decision rule for most categories and benefit/cost analysis for a few categories	• Capable of broad representation of sea level rise scenarios • Optimization of alternatives considering both the impact of adaptation and resulting residual impacts • Rigorous economic costing of adaptation options
	Neumann et al. (2010a): Risks of sea level rise for a portion of the coastal United States	Simulation of adaptation decision making including seawalls, bulkheads, elevation of structures, beach nourishment, and strategic retreat, primarily using a benefit/cost framework but with alternatives based on local land use decision-making rules	• Capable of broad representation of sea level rise scenarios • Flexibility to consider both benefit/cost and rule-based decision making • Rigorous and dynamic economic costing of adaptation options
	Purvis et al. (2008): Risks of coastal flooding in Somerset, England	Simulation using a probabilistic representation to characterize uncertainty in future sea level rise and, potentially, other factors that could affect coastal land use planning and development investment decisions	• Considers the impact of both gradual climate change (sea level rise) and extreme events (the 1-in-200-year recurrence interval coastal flooding event) • Incorporates probabilistic uncertainty analysis
Water	Ward et al. (2010): Future needs and costs for municipal water across the world, scalable to national and local scales	Assesses costs with and without climate change of reaching a water supply target in 2050. The aggregation level used is the food producing units level, and storage capacity change, using the secant peak algorithm to determine the storage yield relationship and the cost of various alternative sources of water. The authors find that baseline costs exceed adaptation costs ($73 billion per year versus $12 billion per year for adaptation), with most of the adaptation costs (83–90%) incurred in developing countries.	• Multiple climate scenarios • Scalable to multiple spatial resolutions, with national and regional results reported • Multiple alternative adaptation options considered • Rigorous economic costing of site-specific capital and operating costs
Urban flooding	Ranger et al. (2011): direct and indirect impacts of flooding in Mumbai, India	Investigates the consequences of floods with different return periods, with and without climate change; the effect of climate change is from a weather generator that downscales simulations from a global climate model. Estimates direct losses from a 100-year event rising from $600 million today to $1890 million in the 2080s, and total losses (including indirect losses) rising from $700 to $2435 million. Impacts give rise to adaptation options, some targeting direct losses (e.g., improved building quality, improved drainage infrastructure) and others targeting indirect losses (e.g., increased reconstruction capacity, micro-insurance). Analysis finds that improved housing quality and drainage could bring total losses in the 2080s below current levels and that full access to insurance would halve indirect losses for large events.	• Considers multiple adaptation options • Explicitly considers both direct and indirect costs • Rigorous economic costing of adaptation options
Energy	Lucena et al. (2010): Energy production in Brazil, particularly from hydropower	Simulation of multiple adaptation options, including energy source substitution and regional "wheeling" of power coupled with modeling of river flow and hydropower production under future climatic conditions. Uses an optimization model of overall energy production.	• Considers two greenhouse gas emissions scenarios and a "no-climate change" baseline • Scalable to multiple spatial resolutions, with national and regional results reported • Considers multiple adaptation strategies • Rigorous economic costing of capital and recurring adaptation costs
Health	Ebi (2008): Global adaptation costs of treatment of diarrheal diseases, malnutrition, and malaria	The costs of three diseases were estimated in 2030 for three climate scenarios using (1) the current numbers of cases; (2) the projected relative risks of these diseases in 2030; and (3) current treatment costs. The analysis assumed that the costs of treatment would remain constant. There was limited consideration of socioeconomic development.	• Multiple climate scenarios • Clear description of framework and key assumptions • Rigorous economic costing of adaptation options using multiple assumptions to characterize uncertainty

Continued next page →

Table 17-4 (continued)

Sector	Study and scope	Methodology	Key points illustrated
Macroeconomic analysis	De Bruin et al. (2009b): Adaptation strategies compared to mitigation strategies within the context of a global integrated assessment model	Use of an integrated assessment model (the DICE model) with refined adaptation functions. Examines the efficacy of "stock" adaptations (mainly infrastructure) adaptations versus "flow" adaptations (mainly operational or market responses), with comparisons to mitigation investments.	• Multiple climate scenarios • Clear description of framework and key assumptions • Considers multiple adaptation strategies • Rigorous economic costing of adaptation options
	Margulis et al. (2011): Climate change impacts in the economy	Use of a general equilibrium model to simulate two climate change-free scenarios regarding the future of Brazil's economy. Climate shocks were projected and captured by the model through impacts on the agricultural/livestock and energy sectors. The socioeconomic trends of the scenarios with and without global climate change were reviewed in terms of benefits and costs for Brazil and its regions.	• The economic impacts of climate change are experienced across business sectors, regions, states, and large cities and were expressed in terms of gross domestic product losses. • The simulation disaggregates results for up to 55 sectors and 110 products and also provides macroeconomic projections such as inflation, exchange rate, household sector consumption, government expenditures, aggregate investment, and exports. It also includes expert projections and scenarios on specific preferences, technology, and sector policies.

supply in response to changes in climatic conditions and agricultural and water resource management techniques. A further advantage of the simulation approach is that it provides an opportunity for stakeholder involvement at several stages of the analytic process: designing scope, adjusting parameters, selecting inputs, calibrating results, and incorporating adaptation measures of specific local interest (Dinar and Mendelsohn, 2011).

A wide range of studies attempt an economic evaluation of adaptation options. From these, several desirable characteristics can be identified:

- A broad representation of climate stressors, including both gradual change and extreme events, spanning multiple future outcomes (e.g., a range of individual climate model forecasts and greenhouse gas emissions scenarios). Consideration of multiple outcomes reflects forecasting uncertainty and can help to ensure the adaptation rankings that result from the analysis are robust across a range of future outcomes (Lempert and Kalra, 2009; Agrawala et al., 2011; see also Chapter 2).
- Representation of a wide variety of alternative adaptation responses (e.g., in the agriculture sector, consideration of changes in crop varieties and farmer education to ensure the varieties are grown with the best available know-how). Depending on the context, single adaptation response with variation in dimension may be useful (e.g., varying the height of a levee or the capacity of a dam spillway) (Fankhauser et al., 1999; Fankhauser, 2010; World Bank, 2010a).
- Rigorous economic analysis of costs and benefits, which ideally includes consideration of market, non-market, and socially contingent implications (Watkiss, 2011); one-time and replacement capital and ongoing recurring costs; and costs of residual damages after an adaptation response is implemented (World Bank, 2010a).
- A strong focus on adaptation decision making, including a clear exposition of the form of adaptation decision making that is implied in the study, and consideration of both climate and non-climate sources of uncertainty (Lempert et al., 2006; see also Chapter 2).

Table 17-4 highlights studies that illustrate some of these characteristics. The studies include both simulation studies of the economic implications of adaptation options, and econometric ones that examine choices that producers make to adapt. These studies generally fall in the category of positive economics, where economic tools and analysis are used to examine the implications of alternative choices without imposing values of the author (see Friedman, 1953). A few studies incorporate a normative perspective, either explicitly or implicitly, reflecting value judgments of authors or study participants.

17.5. Economic and Related Instruments to Provide Incentives

Through regulations, subsidies, and direct intervention, there are many opportunities for policymakers to encourage autonomous adaptation. However, these efforts need to be designed so as to yield efficient, cost-effective responses while avoiding perverse results. A basic issue of designing efficient policies is to understand that they affect the behavior of those who have the most to gain. For this and other reasons, economists tend to favor policies based on voluntary actions influenced by incentives, either positive or negative, over mandates or uniform policies. Examples of these include insurance markets, water markets, and various payments for environmental services (PES) schemes. A second consideration in policy design is cost effectiveness, that is, the extent to which governments make the best use of their resources. The measurement of the net effect of a policy is challenging because it is difficult to anticipate what would have occurred without the policy.

Finally, policies must be carefully designed to avoid perverse outcomes that run counter to the policymaker's objectives. A classic example is found in policies that encourage adoption of water-saving technology. Pfeiffer and Lin (2010) review cases where subsidizing irrigation water conservation leads farmers to increase total water use by increasing the acreage under irrigation. This is an example of what is often called the rebound effect (Roy, 2000), whereby increases in efficiency of resource use result in more being demanded.

With the exception of insurance- and trade-related instruments there is relatively little literature on the use of economic instruments for adaptation (see Chapter 10). One reason is that, apart from insurance, few adaptation policies work directly via economic incentives and markets. The potential of economic instruments in an adaptation context is, however, widely recognized. In line with Agrawala and Fankhauser (2008), we distinguish, among others, the following incentive-providing instruments relevant for key sectors: (1) insurance schemes (all sectors; extreme events); (2) price signals/markets (water, ecosystems); (3) regulatory measures and incentives (building standards, zone planning); and (4) research and development incentives (agriculture, health).

17.5.1. Risk Sharing and Risk Transfer, Including Insurance

Insurance-related formal and informal mechanisms can directly lead to adaptation and provide incentives or disincentives. Informal mechanisms include reliance on national or international aid or remittances, and though such mechanisms are common, they tend to break down for large, covariate events (Cohen and Sebstad, 2005). Another informal mechanism is the inclusion of climate change risk under corporate disclosure regulations (National Round Table on the Environment and the Economy, 2012). Formal mechanisms include insurance, micro-insurance, reinsurance, and risk pooling arrangements. Insurance typically involves ongoing premium payments in exchange for coverage and post event claim payments. In contrast to indemnity-based insurance, index-based insurance insures the event (as, e.g., measured by lack of rainfall), not the loss, and is a possibility for providing a safety net without moral hazard, yet suffers from basis risk, the lack of correlation of loss to event (Collier et al. 2009; Hochrainer et al., 2009; see also Section 10.7 for a supply-side-focused perspective on insurance). Markets differ substantially according to how liability and responsibility is distributed (Aakre et al., 2009; Botzen et al., 2009), and in many instances governments play a key role as regulators, insurers, or reinsurers (Linnerooth-Bayer et al., 2005). Insurance penetration in developed countries is considerable, whereas it is low in many developing regions. In the period 1980–2004 about 30% of losses were insured in high-income countries, but only about 1% in low-income countries (Linnerooth-Bayer et al., 2011). Developing countries are beginning to pool risks and transfer portions to international reinsurance markets. The Caribbean Catastrophic Risk Insurance Facility (CCRIF) set the precedent by pooling risks basin wide, thus reducing insurance premiums against hurricane and earthquake risks (World Bank, 2007). Similar schemes are under development planning in Europe, Africa, and the Pacific (Linerooth-Bayer et al., 2011).

Insurance-related instruments may promote adaptation directly and indirectly: (1) Instruments provide claim payments after an event, and thus reduce follow-on risk and consequences; and (2) they alleviate certain pre-event risks and allow for improved decisions (Hess and Syroka, 2005; Hoppe and Gurenko, 2006; Skees et al., 2008). As one interesting example, using crop micro-insurance linked to loans, farmers exposed to severe drought in Malawi were able to grow higher-yield, yet higher-risk crops, which allowed them to increase incomes (Linnerooth-Bayer and Mechler, 2011).

The indirect effects occur via the provision of incentives and disincentives. Premiums for risk coverage can provide an incentive to reduce the premium by reducing the risk. In practice, the incentive effect is generally weak. Kunreuther et al. (2009) found that insurance decisions are not based solely on costs and premiums, but also desires to reduce anxiety, comply with mortgage requirements, and satisfy social norms. Further, purchasing insurance may reduce adaptation with insured agents reducing their risk-minimizing efforts after taking out coverage. This is termed moral hazard and has been found to be rational (Kunreuther, 1998). Moral hazard can be reduced through the use of index-based insurance, although this has the drawback of operating from a high base risk (Collier et al., 2009; Hochrainer et al., 2009). Another difficulty arises when local or state regulations undermine incentives to decrease risk (for instance, by not allowing insurance rates to be fully risk adjusted). Some analysts suggest the removal of existing regulations that distort market signals in order to re-align incentives, yet this is likely to be ineffective given that the incentive effect is not considered very strong and often premiums are not fully risk-based (Michel-Kerjan and Kunreuther, 2011). Also, Rao and Hess (2009) argue there is the possibility that some current insurance schemes may increase maladaptation. Under-insurance can also arise when agents expect that the public sector will provide disaster assistance. Some refer to this as the Samaritan's dilemma (Gibson et al., 2005; Raschky et al., 2013).

17.5.2. Payments for Environmental Services

Payments for environmental services (PES) pay landholders or farmers for actions that preserve the services to public and environmental health provided by ecosystems on their property, including services that contribute to both climate change adaptation and mitigation. There are ample cases of mitigation-focused PES schemes (e.g., Pagiola, 2008; Wunder and Albán, 2008; Wunder and Borner, 2011), and more recently emerging evidence of the use of PES in adaptation which are of pilot nature and location-specific, however (Butzengeiger-Geyer et al., 2011; Schultz, 2012; van de Sand, 2012). Potentially well designed PES schemes offer a framework for adaptation and there is a view among development agencies that with more experience and guidance on implementation PES might well contribute to adaptation as one of a multitude of feasible measures (e.g., taxes, charges, subsidies, loans). Chishakwe et al. (2012) draw comparisons and find synergies between PES community-based natural resources management approaches in southern Africa and community-based adaptation.

17.5.3. Improved Resource Pricing and Water Markets

Studies of water sector adaptation often begin by citing the implications of future water shortages and the potential for conflict. Techniques frequently cited for resolving these conflicts include the establishment of water markets or water pricing schemes (e.g., Vorosmarty et al., 2000; Adler, 2008; Alavian et al., 2009), which is in itself, however, also often associated with conflict (Miller et al., 1997). Traditionally water markets facilitate transfer from lower to higher-valued uses (Olmstead, 2010) but pricing rules can also function through urban fees and real estate taxes (as they do for water supply and urban stormwater regulation in many countries). A few studies make the case that water markets and pricing improves climate change adaptation (Medellin-Azuara et al., 2008). In many cases, the projected increase in climate-induced water demand (particularly in the agriculture sector), coupled with a projected decrease in water supply, suggests that adaptation will be needed.

Many countries have instituted structures for water pricing in the household and agricultural sectors. Nevertheless such prices are unevenly

Frequently Asked Questions

FAQ 17.3 | In what ways can economic instruments facilitate adaptation to climate change in developed and developing countries?

Economic instruments (EIs) are designed to make more efficient use of scarce resources and to ensure that risks are more effectively shared between agents in society. EIs can include taxes, subsidies, risk sharing, and risk transfer (including insurance), water pricing, intellectual property rights, or other tools that send a market signal that shapes behavior. In the context of adaptation, EIs are useful in a number of ways.

First, they help establish an efficient use of the resources that will be affected by climate change: water pricing is an example. If water is already priced properly, there will be less overuse that has to be corrected through adaptation measures should supplies become more scarce.

Second, EIs can function as flexible, low-cost tools to identify adaptation measures. Using the water supply example again, if climate change results in increasing water scarcity, EIs can easily identify adjustments in water rates needed to bring demand into balance with the new supply, which can be less costly than finding new ways to increase supply.

Insurance is a common economic instrument that serves as a flexible, low-cost adaptation tool. Where risks are well defined, insurance markets can set prices and insurance availability to encourage choices and behaviors that can help reduce vulnerability, and also generate a pool of funds for post-disaster recovery. Insurance discounts for policy holders who undertake building modifications that reduce flood risk, for example, are one way that EIs can encourage adaptive behavior.

Payments for environmental services (PES) schemes are another economic instrument that encourages adaptive behavior. This approach pays landholders or farmers for actions that preserve the services to public and environmental health provided by ecosystems on their property, including services that contribute to both climate change mitigation and adaptation. A PES approach is being used in Costa Rica to manage natural resources broadly, for example. Paying timber owners not to cut down forests that serve as carbon sinks (the idea behind the Reduced Emissions from Deforestation and Forest Degradation (REDD) proposal to the United Nations Framework Convention on Climate Change (UNFCCC)) or paying farmers not to cultivate land in order reduce erosion damage (as is being done in China and the USA) are examples. In developed countries, where markets function reasonably well, EIs can be directly deployed through market mechanisms. In developing countries (and also in some developed ones), however, this is not always the case and markets often need government action and support. For example, private insurance companies sometimes don't cover all risks, or they set rates that are not affordable, and public intervention is required to make sure the insurance is available and affordable. Government also has an important role in ensuring that voluntary market instruments work effectively and fairly, through legal frameworks that define property rights involving scarce resources such as land and water in areas where such rights are not well established. An example of this is the conflict between regions over the use of rivers for water supply and hydropower, when those rivers flow from one jurisdiction to the next and ownership of the water is not clearly established by region-wide agreements. PES schemes can only function well when the public sector ensures that rights are defined and agreements honored.

applied, collection rates are low, metering is rarely implemented (at least for the agricultural sector, which is typically the largest water user), and pricing is often based on annual rather than usage-based fees (Saleth et al., 2012). In many countries, a number of important institutional barriers to water markets and pricing remain. These include a lack of property rights including a thorough consideration of historical and current entitlements, limits on transferability, legal and physical infrastructures, and institutional shortcomings (Turral et al., 2005; Saleth et al., 2012) coupled with issues involved with return flows, third-party impacts, market design, transactions costs, and average versus marginal cost pricing (Griffin, 2012).

17.5.4. Charges, Subsidies, and Taxes

The environmental economics literature over the past 30 years has emphasized the importance of market-based instruments (MBIs) relative to command and control regulations. MBIs are shown to be generally more cost effective, providing stronger incentives for innovation and dynamic efficiency. Within the wide range of instruments that qualify as market based, there is a general preference in terms of overall efficiency for taxes over subsidies (Sterner, 2002; Barbier and Markandya, 2012). MBIs include charges on harmful emissions and wastes, subsidies to clean energy, subsidized loans, and others.

In many cases climate change exacerbates the effects of pricing resources below their social costs. This is true for some forms of energy (e.g., hydro- and fossil fuel-based) as well as many ecosystem services. If these resources were optimally priced, there would be greater incentives to investment in clean technologies and the need for additional public sector adaptation measures would be lessened (ESMAP, 2010).

In addition to the instruments already identified, others that are potentially important include raising the price of energy through a tax (Sterner, 2011), developing markets for genetic resources (Markandya and Nunes, 2012), and strengthening property rights so schemes such as PES can be more effective. These measures are desirable even in the absence of climate change; they become even more so when climate impacts are accounted for. Yet it is important to note that though the case for such social cost pricing through the use of charges is strong, it also has its limitations. Higher prices for key commodities can hurt the poor and vulnerable and complementary measures may need to be taken to address such effects.

17.5.5. Intellectual Property Rights

Technology transfer is increasingly seen as an important means of adaptation because of the global benefits it provides through the transfer of knowledge. Christiansen et al. (2011), in a Technology Needs Assessments carried out in developing countries, list about 165 technological needs related to mitigation and adaptation. Examples include applications to agriculture in Cambodia and Bangladesh and coastal zones in Thailand. In many of these cases patents and other intellectual property protection constrain technology transfer. Patent buy-outs, patent pools, compulsory licenses, and other open source approaches have been used to relax this constraint (Dutz and Sharma, 2012). Patent buy-outs involve third parties (e.g., international financial institutions or foundations) acquiring the marketing rights for a patented product in a developing country. Patent pools represent a group of patent holders who agree to license their individual patents to each other (closed pool) or to any party (open pool). Compulsory licenses are issued by governments and allow patent rights to be overridden in critical situations. For all the above reasons, therefore, it is suggested that limits to technology transfer are limiting climate change adaptation (Henry and Stiglitz, 2010). There is also the view, however, that strong intellectual property (IP) protection in receiving countries is facilitating technology transfer from advanced countries, and the evidence indicates a systematic impact of IP protection on technology transfer through exports, FDI, and technology licensing, particularly for middle-income countries for which the risk of imitation in the absence of such protection is relatively high.

17.5.6. Innovation and Research & Development Subsidies

Subsidies to encourage innovation through research and development (R&D) may be employed as a measure to encourage adaptation investments as well as behavioral change (Bräuninger at al., 2011). Subsidies involve direct payments, tax reductions, or price supports that enhance the rewards from the implementation of an activity (Gupta et al., 2007). There has been some criticism of the efficiency of subsidies in terms of rent seeking and adverse effects on competitiveness (Barbier and Markandya, 2012). They are often poorly targeted and end up getting captured by middle and upper income groups. Moreover, they imply increasing budgetary burdens. Yet they are popular with decision makers and the wider public. Subsidies are today mostly used for reasons other than climate adaptation, and evidence regarding its use for adaptation as well as regarding the incentivizing of adaptation R&D specifically is missing. Popp (2004) is partly an exception, which focuses on subsidies for mitigation. It shows that such subsidies have little impact on their own but they do work to enhance the effects of other instruments such as energy taxes and regulations that mandate improvements in energy efficiency and the use of lower carbon options.

17.5.7. The Role of Behavior

It is well recognized that often human behavior is characterized by bounded rationality, particularly in relation to choices under risk and uncertainty, which affects the effectiveness of incentive-based approaches. Individuals may over- or underestimate risks (Ellsberg, 1961; Kahneman and Tversky, 1979), and may not consistently weigh long-term consequences (Ainslie, 1975). One well documented explanation is that individuals do not fully use available information on risks when they make their choices (Magat et al., 1987; Camerer and Kunreuther, 1989; Hogarth and Kunreuther, 1995). Policies that well consider such risk perceptions and behavioral biases increase their efficiency. For instance, people react differently to abstract information on distant events as opposed to concrete, current, emotionally charged information (Trope and Liberman, 2003). In practice, this can limit the impact of simply communicating "dry," emotion-free information, such as that on flood return periods, and underlines the importance of participatory, reflexive, and iterative approaches to decision support (Fischhoff et al., 1978; Slovic, 1997; Renn, 2008; IRGC, 2010; see also Section 2.1.2).

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18 Detection and Attribution of Observed Impacts

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Executive Summary

Evidence has grown since the Fourth Assessment Report (AR4) that impacts of recent changes in climate on natural and human systems occur on all continents and across the oceans. This conclusion is strengthened both by new and longer term observations and through more extensive analyses of existing data. {18.3-6}

Reported impacts are caused by changes in climate that deviate from historical conditions, irrespective of the driver of climate change. Most reported impacts of climate change are attributed to warming and/or shifts in precipitation patterns. There is also emerging evidence of impacts of ocean acidification. Only some robust attribution studies and meta-analyses link responses in physical and biological systems to *anthropogenic* climate change. {18.1, 18.3-5}

For many natural systems there is new or stronger evidence for substantial and wide-ranging impacts of climate change. These systems include the cryosphere, water resources, coastal systems, and ecosystems on land and in the ocean. {18.3}

Impacts of climate change on the hydrological cycle, and notably the availability of freshwater resources, have been observed on all continents and many islands. Glaciers continue to shrink worldwide, as a result of climate change (*high confidence*), affecting runoff and water resources downstream. Climate change is the main driver of permafrost warming and thawing in both high-latitude and high-elevation mountain regions (*high confidence*). Hydrological systems have changed in many regions because of changing precipitation or melting cryosphere, affecting water resources, water quality, and sediment transport (*medium confidence*). {18.3.1, 18.5, Figure 18-2}

Across all climate zones and continents, the major role of climate change and increasing atmospheric carbon dioxide (CO_2) on terrestrial and freshwater ecosystems has been confirmed by new and stronger evidence on phenology (*high confidence*), productivity (*low confidence*), distribution ranges (*medium confidence*), and other processes, affecting an increasing number of species and ecosystems. The majority of species extinctions and the recession of the Amazon forest cannot be attributed reliably to climate change. Major climate-driven changes occur in the Arctic region (*high confidence*), the boreal forest (*low confidence*), and many freshwater ecosystems (*low* to *high confidence*, region-dependent). {18.3.2, 18.5}

Despite the known sensitivity of coastal systems to sea level rise, local natural and human perturbations preclude a confident detection of sea level-related impacts of climate change. Climate change has had a major role in observed changes in abundance and distribution of many coastal species (*medium confidence*). {18.3.3}

The physical and chemical properties of oceans (including the extent of Arctic sea ice) have changed significantly over the past 6 decades, due to anthropogenic climate change. Marine organisms have moved to higher latitudes and changed their depth distribution or their phenology, mostly as a result of the warming (*high confidence*). Coral reefs have experienced increased mass bleaching and mortality, driven mainly by warming (*high confidence*). {18.3.3-4, 18.5, Table 18-8, Box 18-2}

Substantial new evidence has been collected on sensitivities of human systems to climate change. Climate change-related impacts on human systems are often dominated by effects of changing social and economic factors. {18.4}

Production of wheat and maize globally and in many regional systems has been impacted by climate change over the past several decades (*medium confidence*). The impacts of climate change on rice and soybean have been small in major production regions and globally (*medium confidence*). Crop production has increased in some mid-latitude regions (United Kingdom, Northeast China) (*high confidence*). Evidence of observed climate change impacts on food systems other than agricultural crops and fisheries is limited. {18.4.1}

Economic losses due to extreme weather events have increased globally, mostly due to increase in wealth and exposure, with a possible influence of climate change (*low confidence*). {18.4.3}

There has been a shift from cold- to heat-related mortality in some regions as a result of warming (*medium confidence*), but despite many well-documented sensitivities of human health to other aspects of weather, clear evidence of an additional observed climate change impact on health outcomes is lacking. {18.4.4}

Livelihoods of indigenous peoples in the Arctic have been altered by climate change, through impacts on food security and traditional and cultural values (*medium confidence*). There is emerging evidence of climate change impacts on livelihoods of indigenous people in other regions. {18.4.6, Box 18-5, Table 18-9}

There is emerging literature on the impact of climate change on poverty, working conditions, violent conflict, migration, and economic growth from various parts of the world, but evidence for detection or attribution to climate change remains *limited*. {18.4}

Regional impacts of climate change have now been observed at more locations than before, on all continents and across ocean regions. In many regions, impacts of climate change are now detected also in the presence of strong confounding factors such as pollution or land use change. {18.6.2}

"Cascading" impacts of climate change from physical climate through ecosystems on people can now be detected along chains of evidence. Examples include systems in the cryosphere, the oceans, and forests. In these cases, confidence in attribution to observed climate change decreases for effects further down the impact chain. {18.6.3}

Evaluation of observed impacts of climate change supports risk assessment of climate change for four of the "Reasons for Concern" developed by earlier IPCC assessments. (1) Impacts related to *Risks to Unique and Threatened Systems* are now manifested for several systems (Arctic, glaciers on all continents, warm-water coral systems). (2) High-temperature spells have impacted one system with *high confidence* (coral reefs), indicating *Risks Associated with Extreme Weather Events*. Elsewhere, extreme events have caused increasing impacts and economic losses, but there is only *low confidence* in attribution to climate change for these. (3) Though impacts of climate change have now been documented globally with unprecedented coverage, observations are still insufficient to address the spatial or social disparities underlying the *Risks Associated with the Distribution of Impacts*. (4) *Risks Associated with Aggregated Impacts*: large-scale impacts, indicated by unified metrics, have been found for the cryosphere (ice volume, *high confidence*), terrestrial ecosystems (net productivity, carbon stocks, *medium-high confidence*), and human systems (crop yields, disaster losses, *low-medium confidence*). (5) R*isks Associated with Large-Scale Singular Events*: impacts that demonstrate irreversible shifts with significant feedback potential in the Earth system have yet to be observed, but there is now *robust evidence* of early warning signals in observed impacts of climate change that indicate climate-driven large-scale regime shifts for the Arctic region and the tropical coral reef systems. {18.6.4}

Though evidence is improving, there is a persistent gap in the knowledge regarding how certain parts of the world are being affected by observed climate change. Data collection and monitoring are in need to gain wider coverage. Research to improve the conceptual basis, timeliness, and knowledge about detection and attribution is needed in particular for human systems. {18.2, 18.7}

18.1. Introduction

This chapter synthesizes the scientific literature on the detection and attribution of observed changes in natural and human systems in response to observed recent climate change. For policy makers and the public, detection and attribution of observed impacts will be a key element to determine the necessity and degree of mitigation and adaptation efforts. For most natural and essentially all human systems, climate is only one of many drivers that cause change—other factors such as technological innovation, social and demographic changes, and environmental degradation frequently play an important role as well. Careful accounting of the importance of these and other confounding factors is therefore an important part of the analysis.

At any given location, observed recent climate change has happened as a result of a combination of natural, longer term fluctuations and anthropogenic alteration of forcings. To inform about the sensitivity of natural and human systems to ongoing climate change, the chapter assesses the degree to which detected changes in such systems can be attributed to all aspects of recent climate change. For the development of adaptation policies, it is less important whether the observed changes have been caused by anthropogenic climate change or by natural climate fluctuations. Where possible, the relative importance of anthropogenic drivers of climate change is assessed as well.

18.1.1. Scope and Goals of the Chapter

Previous assessments, notably in the IPCC Fourth Assessment Report (AR4; Rosenzweig et al., 2007), indicated that numerous physical and biological systems are affected by recent climate change. Owing to a limited number of published studies, human systems received comparatively little attention in these assessments, with the exception of the food system, which is a coupled human-natural system. This knowledge base is growing rapidly, for all types of impacted systems, but the disequilibrium remains (see also Section 1.1.1, Figure 1-1). The great majority of published studies attribute local to regional changes in affected systems to local to regional climate change.

The objective of the assessment was to cover the growing knowledge about detection and attribution of impacts as exhaustively as possible. To improve coverage across sectors and regions, the work was linked directly to the assessments made by most other chapters of the report. This ensured that knowledge gained in the expert assessments of any given sector, system, or region found its way into this chapter. This chapter uses a consistent set of definitions for detection and attribution (elaborated in Section 18.2.1—these differ from those found in some other chapters).

This chapter first reviews methodologies and definitions for detection and attribution, including the uncertainties that are inherent in such assessments (Section 18.2). It then assesses the scientific knowledge base that has developed since the AR4, focusing on the different types of impacted systems. The assessment covers the state of knowledge across major natural (Section 18.3) and human systems (Section 18.4), based largely on the respective sectoral chapters of this report (Chapters 3 to 7, 10 to 13). Assessment in confidence of the existence and cause of impacts is made according to the definitions elaborated in Section 18.2.1.2. Based on this material, and on regional assessments mostly drawn from the regional chapters of this report (Chapters 22 to 30), an assessment is made to highlight regional impacts and also to identify the regional pattern of observed impacts around the globe (Section 18.5). A synthesis (Section 18.6) and an analysis of research and knowledge gaps (Section 18.7) conclude the chapter.

18.1.2. Summary of Findings from the Fourth Assessment Report

Based on Rosenzweig et al. (2007), IPCC (2007a, p. 8) reported that "observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases." In particular, they highlighted several areas where this general conclusion was supported by specific conclusions that were reported with *high confidence*:

- Changes in snow, ice, and frozen ground had increased ground instability in mountains and other permafrost regions; these changes had led to changes in some Arctic and Antarctic ecosystems and produced increases in the number and size of glacial lakes.
- Some hydrological systems had been affected by increased runoff and earlier spring peak discharges; in particular many glacier- and snow-fed rivers and lakes had warmed, producing changes in their thermal structures and water quality.
- Spring events had appeared earlier in the year so that some terrestrial ecosystems had moved poleward and upward; these shifts in plant and animal ranges were attributed to recent warming.
- Shifts in ranges and changes in algal, plankton, and fish abundance as well as changes in ice cover, salinity, oxygen levels, and circulation had been associated with rising water temperatures in some marine and freshwater systems.

In terms of a global synthesis, this assessment noted "that it is *likely* that anthropogenic warming over the last three decades has had a discernible influence on many physical and biological systems" (IPCC, 2007a, p. 9). Though it was based on analyses of a very large number of observational data sets, the assessment noted a lack of geographic balance in data and literature on observed changes, with marked scarcity in low- and middle-income countries.

Evidence reported for human systems was scarce. IPCC (2007a, p. 9) concluded with *medium confidence* only that, "other effects of regional climate change on […] human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers." They especially noted effects of temperature increases on agricultural and forestry management practices in the higher latitudes of the Northern Hemisphere (NH), various aspects of human health, and some human activities in snow- and glacier-dominated environments.

18.2. Methodological Concepts for Detection and Attribution of Impacts of Climate Change

There are substantial challenges to the detection and assessment of the impacts of climate change on natural and human systems. Virtually all such systems are affected by factors other than climate change. Isolating the impacts of climate change therefore requires controlling for the effects of other factors. The problem is further complicated by the ability of many systems to adapt to climate change. In this section we summarize the concepts underlying the detection and attribution of impacts of climate change and the requirements for addressing the main challenges.

18.2.1. Concepts and Approaches

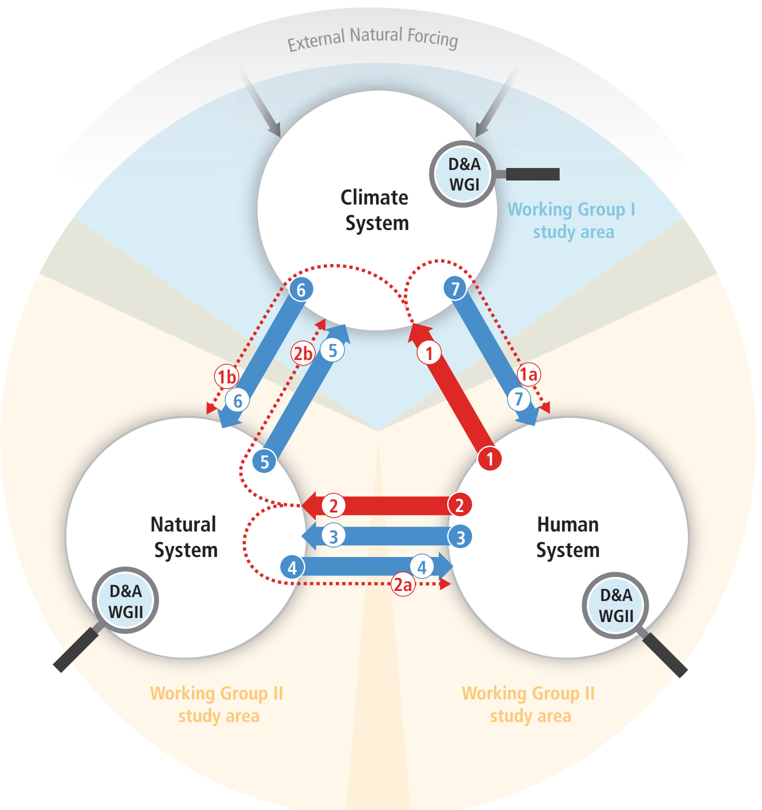
18.2.1.1. Detecting and Attributing Change in the Earth System

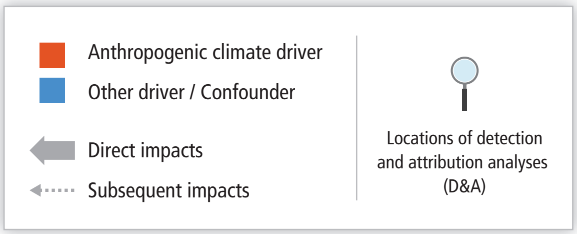
Detection and attribution is concerned with assessing the causal relationship between one or more drivers and a responding system. From an analysis perspective, the Earth system can be separated into three coupled subsystems, referred to here as the climate system, the natural system, and the human system (Figure 18-1). Separation of drivers from a responding system is a crucial element of formal detection and attribution analysis. Many external drivers may influence any system, including the changing climate and other confounding factors (Hegerl et al., 2010). Each of the three subsystems affects the other two directly or indirectly. For example, the human system may directly affect the natural system through deforestation, which in turn affects the climate system through changes in albedo; this can alter surface temperatures, which in turn feed back on natural and human systems. If an observed change in the human system impacts the climate system, we call this an anthropogenic driver of climate change.

In this chapter we assess the impacts of *climate change*, where climate change refers to any long-term trend in climate, irrespective of its cause (see Glossary). The great majority of published scientific studies support this type of assessment only. Some studies directly address the detection of and attribution to *anthropogenic climate change*, relating observed impacts, via the climate, to anthropogenic emissions of greenhouse gases and other human activities. Because of the complexity of the causal chain, investigation of this relationship is exceptionally challenging (Parmesan et al., 2011). The findings from such studies are explicitly highlighted in the chapter.

18.2.1.2. Concepts of Detection and Attribution of Climate Change Impacts Used in this Chapter

"Detection of impacts" of climate change addresses the question of whether a natural or human system is changing beyond a specified baseline that characterizes its behavior in the absence of climate change (Stone et al., 2013). The baseline may be stationary or non-stationary (e.g., due to land use change), and needs to be clearly defined. This definition of the detection of climate change impacts differs from that in WGI AR5 Chapter 10 which concerns any change in a climate variable, regardless of its cause. The definition adopted here focuses explicitly





Example of drivers	Example of Impacts	
	Direct impacts	Subsequent impacts
1 Emission of CO_2	1 Warming	1a Altered crop yield 1b Shift in species phenology
2 Emission of CO_2	2 Carbon fertilization of plants	2a Increase in forestry yield 2b Change in humidity
3 Pollution of river catchment	3 Fisheries collapse	
4 Plague of crop pests	4 Decrease in crop yield	
5 Forest fire	5 Change in humidity	
6 El Nino event	6 More wildfires	
7 El Nino event	7 Crop Failures	

Figure 18-1 | Schematic of the subject covered in this chapter. The Earth system consists of three coupled and overlapping systems. Direct drivers of the human system on the climate system are denoted with a red arrow; some of these drivers may also directly affect natural systems. These effects can in turn influence other systems (dashed red arrows). Further influences of each of the systems on each other (confounding factors) that do not involve climate drivers are represented by blue arrows. Examples of drivers and their impacts are given in the table. Adapted from Stone et al. (2013).

Box 18-1 | Quantitative Synthesis Assessment of Detection and Attribution Studies in Ecological Systems

The wealth of observations in ecological systems now permits the application of quantitative tools for synthesis assessment of detection and attribution (Root et al., 2005). These tools include associative pattern analyses (e.g., Rosenzweig et al., 2008) and regression analyses (Chen, I.C. et al., 2011), which compare expected changes due to anthropogenic climate change across multiple studies against observed changes.

Quantitative synthesis assessments have been particularly prominent in ecology, where measures of phenology (timing of seasonal events) and geographical range can be assembled across species into standardized indices (Parmesan and Yohe, 2003; Rosenzweig et al., 2008; Chen, I.C. et al., 2011; Poloczanska et al., 2013; Rosenzweig and Neofotis, 2013). Confidence in the detection of general patterns of change in these indices can increase with the number of species/ecosystems observed, the number of independent studies, the geographical distribution of these observations, the temporal depth and resolution of the data, and the representativeness of species/ecosystems and locations studied. However, increasing spatial coverage, numbers of species, and so forth does not *a priori* increase confidence that climate change is a more credible explanation for biological change than alternative hypotheses. Additional data can contribute to increased confidence in causal relationships, that is, attribution, in a synthesis assessment when it provides new evidence for explicit testing against a credible range of alternative hypotheses.

on the impact of climate change and not on trends related to other factors. The statement of detection is binary: an impact has or has not been detected.

18

"Attribution" addresses the question of the magnitude of the contribution of climate change to a change in a system. In practice, an attribution statement indicates how much of the observed change is due to climate change with an associated confidence statement. Hence, attribution requires the evaluation of the contributions of all external drivers to the system change. In this chapter we simplify the assessment of this relative contribution by specifying whether observed climate change has had a "minor role" or a "major role" in the overall change in the impacted system. A major role is assessed if the past behavior of the system would have been grossly different in the absence of the observed climate change.

18.2.2. Challenges to Detection and Attribution

Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high-quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question (see also Box 18-1). These processes can be nonlinear—for example, involving threshold effects (e.g., De Young and Jarre, 2009; Wassmann and Lenton, 2012)—and non-local in both space and time, involving lagged responses and trans-regional effects due, for example, to trade or migration.

Conclusions about the effect of climate change on natural and human systems in this report are based on a synthesis of findings in the scientific literature. A potential problem arises through the preferential publication of papers reporting statistically significant findings (Parmesan and Yohe, 2003). Methods exist for detecting and correcting for publication bias in formal quantitative synthesis analysis (Rothstein et al., 2005; Menzel et al., 2006), but these methods cannot be applied in all situations (Kovats et al., 2001). While the assessment in this chapter considers findings in the context of consistency across studies, regions, and similar systems, it has not been possible to quantitatively account for selection bias and to fully differentiate it from the lack of monitoring for some regions and systems.

18.3. Detection and Attribution of Observed Climate Change Impacts in Natural Systems

The following section provides a synthesis of findings with regard to freshwater resources, terrestrial and inland water systems, coastal systems, and oceans, which are documented in greater detail in Chapters 3, 4, 5, 6, and 30, respectively. It also incorporates evidence from regional chapters and further available literature.

18.3.1. Freshwater Resources

Impacts of climate change on the hydrological cycle, and notably the availability of freshwater resources, have been observed on all continents and many islands, with different characteristics of change in different regions (Chapters 3, 22 to 29; WGI AR5 Chapters 2 and 10). Figure 18-2 presents a synthesis of confidence in detection of global scale changes in freshwater resources and related systems (notably slope stability and erosion), and their attribution to climate change. Frozen components of freshwater systems tend to show higher confidence in detection and attribution, while components that are strongly influenced by non-climatic drivers, such as river flow, have lower confidence.

18.3.1.1. The Cryosphere

Most components of the cryosphere (glaciers, ice sheets, and floating ice shelves; sea, lake, and river ice; permafrost and snow) have undergone significant changes during recent decades (*high confidence*), related to climatic forcing (*high confidence*; WGI AR5 Chapter 4). It is *likely* that there is an anthropogenic component in the changes observed in Arctic sea ice, Greenland's surface melt, glaciers, and snow cover (WGI AR5 Section 10.5). Glaciers continue to shrink worldwide, with regional variations. It is *likely* that a substantial part of the glacier mass loss is due to anthropogenic warming (WGI AR5 Section 10.5.2.2). Climate change has a major role in the absolute contribution of ice loss from glaciers and ice caps to sea level rise, which has increased since the early 20th century and has now been close to 1 mm yr^{-1} for the past 2 decades (WGI AR5 Sections 4.3.3, 4.4.3), around a third of total observed sea level rise. Recent mass loss of ice sheets and glaciers has accelerated isostatic land uplift in the North Atlantic Region (Jiang et al., 2010). In several high-mountain regions, slope instabilities have occurred as a consequence of recent glacier downwasting (*high confidence*; Vilímek et al., 2005; Haeberli and Hohmann, 2008; Huggel et al., 2011).

The role of climate in changes in runoff decreases from major to minor as the distance from glaciers increases and other non-climatic factors become more important. Runoff from glacier areas has increased for catchments in western and southwestern China over the past several decades, and in western Canada and Europe (Collins, 2006; Zhang, Y. et al., 2008; Moore et al., 2009; Li et al., 2010; Pellicciotti et al., 2010; Stahl et al., 2010). Glacier runoff has decreased in the European Alps (Collins, 2006; Huss, 2011), in the central Andes of Chile (Casassa et al., 2009), and in the Cordillera Blanca (Baraer et al., 2012; *medium confidence*), a trend that has also been confirmed by qualitative observations made by local people (Bury et al., 2010; Carey et al., 2012a). For lake and river ice, there is generally *high confidence* in detection of, and a major role of climate change in, later freeze-up and earlier break-up over the past 100+ years for several sites in the NH, yet with regional differences and warmer regions showing higher sensitivities in interannual variability (Livingstone et al., 2010; Voigt et al., 2011; Weyhenmeyer et al., 2011; Benson et al., 2012). Changes in lake and river ice can have effects on freshwater ecosystems, transport and traffic over frozen lakes and rivers, and ice-induced floods during freeze-up and break-up events (Voigt et al., 2011). Some evidence exists in Europe that ice-jam floods were reduced during the last century due to reduced freshwater freezing (Svensson et al., 2006).

The rate of Arctic sea ice decline has increased significantly during the first decade of the 21st century, due to warming (WGI AR5 Section 4.2.2). It is *very likely* that at least some of the decline in Arctic sea ice extent can be attributed to anthropogenic climate forcing (WGI AR5 Section 10.5.1). Observations by Inuit people in the Canadian Arctic confirm with *high confidence* the instrumental observations on the various changes of sea ice (see Box 18-5). Antarctic sea ice has slightly increased over the past 30 years, yet with strong regional differences (WGI AR5 Section 4.2.3).

Combined *in situ* and satellite observations indicate a decline of 8% in NH spring snow cover extent since 1922 (WGI AR5 Section 4.5.2). A limited number of studies indicate an anthropogenic influence on snow cover reduction (*high confidence*; WGI AR5 Section 10.5.3), including a significant contribution of anthropogenic climate forcing on changes in snow pack and runoff timing between 1950 and 1999 in the western USA (Table 18-6; Barnett et al., 2008).

Climate change generally exerts a major role on permafrost changes. Widespread permafrost warming and thawing, and active layer thickening

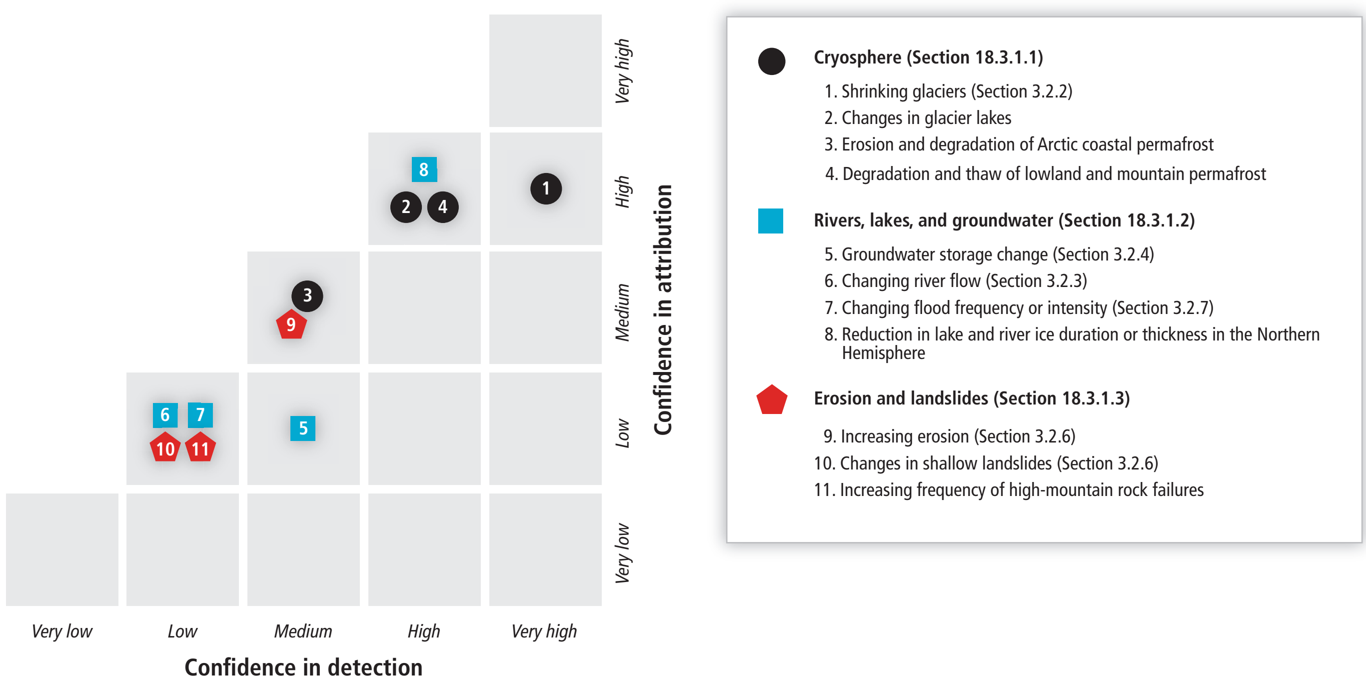


Figure 18-2 | Assessment of confidence in detection of observed climate change impacts in global freshwater systems over the past several decades, with confidence in attribution of a major role of climate change, based on expert assessment contained in Section 18.3.1 and augmented by subsections of Chapter 3 as indicated.

in both high-latitude lowlands and high-elevation mountain regions, have been observed over the past decades (*high confidence*; WGI AR5 Section 4.7.2). Climate change impacts have been related to permafrost changes, including an increase of flow speed of rock glaciers and debris lobes in the European Alps and Alaska (*high confidence*), resulting in rockfall, debris flows, and potential hazards to transport and energy systems (Kääb et al., 2007; Delaloye et al., 2010; Daanen et al., 2012), expansion, deepening and higher dynamics of thermokarst lakes and ponds in the Arctic (Rowland et al., 2010), and a doubled erosion rate of Alaska's northern coastline over the past 50 years (*high confidence*; Section 18.3.3.1, Table 18-8; Mars and Houseknecht, 2007; Karl et al., 2009; Forbes, 2011). Expansion of channel networks (Toniolo et al., 2009), increased river bank erosion (Costard et al., 2007), and an increase in hillslope erosion and landsliding in northern Alaska since the 1980s (Gooseff et al., 2009) have all been related to climate. Warming and thawing of permafrost in Alaska has adversely affected transport and energy structures and their operation (Karl et al., 2009). Feedbacks and interactions complicate detection of drivers and effects. For example, drying of land surface due to permafrost degradation may cause an increase in wildfires, in turn resulting in a loss of ground surface insulation and change in surface albedo that accelerates permafrost thawing (Rowland et al., 2010; Forkel et al., 2012).

18.3.1.2. The Regional Water Balance

The regional water balance is the net result of gains (precipitation, ice and snow melt, river inflow, and groundwater recharge) and losses (evapotranspiration, water use and river outflow, and groundwater discharge). Impacts of climate change include reduced availability of freshwater for use (one of the variables defining drought) or excess water (floods). Evapotranspiration, being a function of solar radiation, surface temperature, vegetation cover, soil moisture, and wind, is affected by the changing climate, but also by changing vegetation processes and land cover. At the global scale, human influence has contributed to large-scale changes in precipitation patterns over land and, since the mid-20th century, in extreme precipitation (*medium confidence*; WGI AR5 Section 10.6.1.2; Min et al., 2011). More locations worldwide have experienced an increase than a decrease in heavy rainfall events, yet with significant regional and seasonal variations (Seneviratne et al., 2012; Westra et al., 2013). In some regions, however, there is *medium confidence* that anthropogenic climate change has affected streamflow and evapotranspiration (WGI AR5 Section 10.3.2.3).

Change in river flow is a direct indicator of a changing regional water balance. Globally, about one-third of the top 200 rivers (ranked by river flow) show statistically significant trends during 1948–2004, with more rivers having reduced flow (45) than rivers with increased flow (Dai et al., 2009). Regional reductions in precipitation in southwestern South America are primarily due to internal variability (Dai, 2011; see also Section 27.2.1.1). River floods, defined as impacts caused by the over-topping of river banks and levées, have shown statistically significant increasing and decreasing trends in some regions. The role of climate change in these changes is uncertain, as they may reflect decadal climate variability and be affected by other confounding factors such as human alteration of river channels and land use (Section 3.2.7). In regions with detected increases in heavy rainfall events (North America, Europe), both increases and decreases in floods have been found (*medium confidence* in detection; Petrow and Merz, 2009; Villarini et al., 2009). In the UK, flood risk has increased due to anthropogenic forcing for events comparable to the 2000 floods (Kay et al., 2011; Pall et al., 2011; see also Section 18.4.3).

Expanding or new lakes as a result of ice melt at the margin of many shrinking glaciers in the Alps of Europe, Himalayas, Andes, and other mountain regions have altered the risk of glacier lake outburst floods (GLOFs) and required substantial risk reduction measures in the 21st century (Huggel et al., 2011; Carey et al., 2012b). Though there is no evidence for a change in frequency or magnitude of GLOFs (Seneviratne et al., 2012), climate change has had a major role in the substantial increase in glacial lake area in the eastern Himalaya region between 1990 and 2009 (Gardelle et al., 2011), and the similarly strong increase in lake numbers in the Andes of Peru in the second half of the 20th century (Carey, 2005), and in northern Patagonia from 1945 to 2011 (Loriaux and Casassa, 2013; *high confidence* in detection). New glacier lakes are not only an additional source of floods but also have become a tourist attraction, led to additional infrastructure, and stimulated assessment of potential for hydropower generation (Terrier et al., 2011).

Since the 1950s some regions of the world have experienced more intense and longer droughts, although a global trend currently cannot be established (Seneviratne et al., 2012; see also Section 3.2.2 and WGI AR5 Section 2.6.2.3). Longer drought periods have affected groundwater recharge (Leblanc et al., 2009; Taylor et al., 2013), but changes in groundwater storage are generally difficult to attribute to climate change, due to confounding factors from human activities (Table 3-1; Rodell et al., 2009; Taylor et al., 2013). Likewise, confounding factors do not permit attribution of observed changes in water quality to climate change (Kundzewicz and Krysanova, 2010; see also Section 3.2.5).

18.3.1.3. Erosion, Landslides, and Avalanches

Erosion and landsliding typically increase in phase with deglaciation in mountain areas (Ballantyne, 2002; Korup et al., 2012), and there is emerging evidence for this to occur during contemporary deglaciation (Schneider et al., 2011; Uhlmann et al., 2013). In the western Himalaya, sediment flux has increased (*medium confidence*; Wulf et al., 2012) and been related to hydrologic extreme events over the past 60 years (*low confidence*; Malik et al., 2011), with important consequences for hydropower schemes. In China, a drastic decrease of sediment load in the Yangtze River was observed since the 1980s. There have been local variations in precipitation and runoff since 1950, but changes in sediment load are attributed primarily to more than 50,000 dams and vegetation changes (*medium confidence*; Xu et al., 2008). There is clear evidence for decline in sediment load in the Zhujiang (Pearl River) basin since the early 1990s (Zhang, S. et al., 2008).

In the European Alps, no clear evidence exists so far for any change in frequency of shallow landslides and debris flows from recently deglaciated mountain areas (Jomelli et al., 2004; Stoffel and Huggel, 2012). In some cases climate change has had a major role in influencing frequency and magnitude of alpine shallow landslides and debris flows by altering sediment yield, for example, from rockfall or disintegration of rock glaciers (*low confidence*; Lugon and Stoffel, 2010).

Glacier shrinkage, permafrost degradation, and high-temperature events have contributed to many high-mountain rock slope failures since the 1990s (*medium confidence* in major role of climate change; Allen et al., 2010; Ravanel and Deline, 2011; Schneider et al., 2011; Fischer et al., 2012; Huggel et al., 2012a). Rock slope failures have increased over this period in the Western Alps of Europe (*high confidence*), the New Zealand Alps (*medium confidence*), and globally (*low confidence*). Cascading processes of permafrost and ice-related landslides impacting lakes and downstream areas have been observed in many high-mountain regions, causing major damages and risk reduction measures (*high confidence*), with climate change exerting a major role (*medium confidence*; e.g., Xin et al., 2008; Bajracharya and Mool, 2009; Künzler et al., 2010; Carey et al., 2012a; Huggel et al., 2012b). For landslide types other than the above, there is no clear evidence that their frequency or magnitude has changed over the past decades (Huggel et al., 2012b). In general, detection of changes in the occurrence of landslides is complicated by incomplete inventories, both in time and space, and inconsistency in terminology.

Physical understanding suggests that climate change has a major role in changes of snow avalanche activity but no such changes have been reported so far (*medium confidence*; Laternser and Schneebeli, 2002; Voigt et al., 2011), except for the French Alps (Eckert et al., 2013; *medium confidence* in detection). The detection of changes in snow avalanche impacts, such as fatalities and property loss, is difficult over the past decades because of changes in snow sport activities and avalanche defense measures.

18.3.2. Terrestrial and Inland Water Systems

As documented by previous IPCC reports (notably Rosenzweig et al., 2007), climate-driven changes in terrestrial and inland water systems are widespread and numerous. Confidence in such detection of change is often *very high*, reflecting *high agreement* among many independent sources of evidence of change, and *robust evidence* that changes in ecosystems or species are outside of their natural variation. Confidence in attribution to climate change is also often *high*, due to process understanding of responses to climate change, or strong correlations with climate trends and where confounding factors are understood to have limited importance (Sections 4.3.2, 4.3.3, Figure 4-4). The scientific literature in this field is growing quickly; detailed traceability is provided in Chapter 4.

Organisms respond to changing climate in a multitude of ways, including through their phenology (the timing of key life history events such as flowering in plants or migration of birds), productivity (the assimilation of carbon and nutrients in biomass), spatial distribution, mortality/extinction, or by invading new territory. Noticeable changes may occur at the level of individual organisms, ecosystems, landscapes, or by modification of entire biomes. Organisms and ecosystems are adapted to a variable environment, and they are capable of adapting to gradual change to some degree. Assessing confidence in the detection of such change therefore involves assumptions about natural variability in these ecosystems, while assessment of confidence in the attribution of detected change to climate drivers (or carbon dioxide (CO_2)) implies the assessment of confounding drivers such as pollution or land use change.

18.3.2.1. Phenology

Since the AR4 there has been a further substantial increase in observations, showing that hundreds of (but not all) species of plants and animals have changed functioning to some degree over the last decades to centuries on all continents (*high confidence* due to *robust evidence* but only *medium agreement* across all species; Section 4.3.2.1; Menzel et al., 2006; Cook et al., 2012b; Peñuelas et al., 2013). New satellite-based analyses confirm earlier trends, showing, for example, that the onset of the growing season in the NH has advanced by 5.4 days from 1982 to 2008 and its end has been delayed by 6.6 days (Jeong et al., 2011). Significant changes have been detected, by direct observation, for many different species, for example, for amphibians (e.g., Phillimore et al., 2010), birds (e.g., Pulido, 2007; Devictor et al., 2008), mammals (e.g., Adamík and Král, 2008), vascular plants (e.g., Cook et al., 2012a), freshwater plankton (Adrian et al., 2009), and others (Section 4.3.2.1); a number of new meta-analyses have been carried out summarizing this literature (e.g., Cook et al., 2012a). Attribution of these changes to climate change is supported by more refined analyses that consider also the regional changes in several variables such as temperature, growing season length, precipitation, snow cover duration, and others, as well as experimental evidence (Xu et al., 2013). The *high confidence* in attributing many observed changes in phenology to changing climate is a result of these analyses, as well as of improved knowledge of confounding factors such as land use and land management (see also Section 4.3.2.1).

18.3.2.2. Productivity and Biomass

Many terrestrial ecosystems are now net sinks for carbon over much of the NH and also in parts of the Southern Hemisphere (*high confidence*; see also Sections 4.3.2.2-3). This is shown, for example, by inference from atmospheric chemistry, but also by direct observations of increased tree growth in many regions including Europe, the USA, tropical Africa, and the Amazon. During the decade 2000 to 2009, global land net primary productivity was approximately 5% above the preindustrial level, contributing to a net carbon sink on land of 2.6 ± 1.2 PgC yr^{-1} (Section 4.3.2.2; WGI AR5 6.3.2.6; for primary literature, see also Raupach et al., 2008; Le Quéré et al., 2009), despite ongoing deforestation. Forests have increased in biomass for several decades in Europe (Luyssaert et al., 2010) and the USA (Birdsey et al., 2006). These trends are in part due to nitrogen deposition, afforestation, and altered land management which makes direct attribution of the increase to climate change difficult. The degree to which rising atmospheric CO_2 concentrations contribute to this trend remains a particularly important source of uncertainty (Raupach et al., 2008). Canadian managed forests increased in biomass only slightly during 1998-2008, because growth was offset by significant losses due to fires and beetle outbreaks (Stinson et al., 2011). In the Amazon forest biomass has generally increased in recent decades, dropping temporarily after a drought in 2005 (Phillips et al., 2009). A global analysis of long-term measurements suggests that soil respiration has increased over the past 2 decades by approximately

0.1 PgC yr^{-1}, some of which may be due to increased productivity (Bond-Lamberty and Thomson, 2010). Man-made impoundments in freshwater ecosystems represent an increasing and short-lived additional carbon store with conservative annual estimates of 0.16 to 0.2 PgC yr^{-1} (Cole et al., 2007).

18.3.2.3. Species Distributions and Biodiversity

Each species responds differently to a changing environment; therefore the composition of species, genotypes, communities, and even ecosystems varies in different ways from place to place, in response to climate change. The consequences are changing ranges of species, changing composition of the local species pool, invasions, mortality, and ultimately extinctions. For different species and species groups, detected range shifts vary, and so do the confidence of detection and the degree of attribution to climate change. The number of species studied has considerably increased since the AR4. Overall, many terrestrial species have recently moved, on a global average, 17 km poleward and 11 m up in altitude per decade (e.g., Europe, North America, Chile, Malaysia), which corresponds to predicted range shifts due to warming (Chen, I.C. et al., 2011) and is two to three times faster than previous estimates (Parmesan and Yohe, 2003; Fischlin et al., 2007), with *high confidence* in detection. Europe forest species are moving up in altitude, probably due to climate warming at the end of the 20th century (Gehrig-Fasel et al., 2007; Lenoir et al., 2008). Species with short life cycles and high dispersal capacity—such as butterflies (*high confidence* in a major role of climate change)—are generally tracking climate more closely than longer-lived species or those with more limited dispersal such as trees (Devictor et al., 2012; *medium confidence* in a major role of climate change). There are many less well-studied species for which detection of change and its attribution to climate change are more uncertain.

Changes in abundance, as measured by changes in the population size of individual species or shifts in community structure within existing range limits, have occurred in response to recent global warming (Thaxter et al., 2010; Bertrand et al., 2011; Naito and Cairns, 2011; Rubidge et al., 2011; Devictor et al., 2012; Tingley et al., 2012; Vadadi-Fülöp et al., 2012; Cahill et al., 2013; Ruiz-Labourdette et al., 2013), but owing to confounders, confidence in a major role of climate change is often *low*. Across the world, species extinctions are at or above the highest rates of species extinction in the fossil record (*high confidence*; Barnosky et al., 2011). However, only a small fraction of observed species extinctions have been attributed to climate change—most have been ascribed to non-climatic factors such as invasive species, overexploitation, or habitat loss (Cahill et al., 2013). For those species where climate change has been invoked as a causal factor in extinction (such as for the case of Central American amphibians), there is *low agreement* among investigators concerning the importance of climate variation in driving extinction and even less agreement that extinctions were caused by climate change (Pounds et al., 2006; Kiesecker, 2011). Confidence in the suggested attribution of extinctions across all species to climate change is *very low* (see also Section 4.3.2.5).

Species invasions have increased over the last several decades worldwide, notably in freshwater ecosystems (*very high confidence*), often causing biodiversity loss or other negative impacts. There is only *low confidence* that species invasions have generally been assisted by recent climatic trends because of the overwhelming importance of human facilitated (intentional or non-intentional) dispersal in the transfer from the area of origin. Once established in a new environment, many introduced species have recently become invasive due to climate change (*medium* to *high confidence*, depending on the taxon; see also Section 4.2.4.6).

18.3.2.4. Impacts on Major Systems

Field and satellite measurements indicate substantial changes in freshwater and terrestrial ecosystems (often linked to permafrost thawing) in many areas of the Arctic tundra (*high confidence*; Hinzman et al., 2005; Axford et al., 2009; Jia et al., 2009; Post et al., 2009; Prowse and Brown, 2010; Myers-Smith et al., 2011; Walker et al., 2012). Vegetation productivity has systematically increased over the past few decades in both North America and northern Eurasia (Goetz et al., 2007; Jia et al., 2009; Elmendorf et al., 2012). Most subpopulations of the polar bear are declining in number (Vongraven and Richardson, 2011). These changes correspond to expectations, based on experiments, models, and paleoecological responses to past warming, of broad-scale boreal forest encroachment into tundra, a process that takes decades and that would have very large impacts on ecosystem structure and function. The particular strength of warming over the last 50 years for most of the Arctic further facilitates attribution of a major role of climate change (*high confidence*). The change affects a significant area of the tundra biome and can be considered an early warning for an ongoing regime shift (Section 4.3.3.4, Figure 4-4).

For the boreal forest, increases in tree mortality are observed in many regions, including widespread dieback related to insect infestations and/or fire disturbances in North America (Fauria and Johnson, 2008; Girardin and Mudelsee, 2008; Kasischke et al., 2010; Turetsky et al., 2010; Wolken et al., 2011) and in Siberia (Soja et al., 2007), but there is *low confidence* in detection of a global trend. Many areas of boreal forest have experienced productivity declines (*high confidence*; Goetz et al., 2007; Parent and Verbyla, 2010; Beck and Goetz, 2011), related to warming-induced drought, specifically the greater drying power of air (Williams et al., 2012), inducing photosynthetic down-regulation of boreal tree species not adapted to the warmer conditions (Welp et al., 2007; Bonan, 2008). Conversely, productivity has increased along the boreal-tundra ecotone where more mesic (moist) conditions may be generating the expected warming-induced positive growth response (McGuire et al., 2007; Goldblum and Rigg, 2010; Beck and Goetz, 2011). Overall, these multiple impacts in the boreal forest biome can be considered an early warning for an ongoing regime shift only with *low confidence* (Section 4.3.3.1.1, Figure 4-4). Many of the aforementioned changes take place in the tundra-boreal ecotone, affecting both biomes significantly (Box 4-4, Figure 4-10).

In tropical forests, climate change effects are difficult to identify against the confounding effects of direct human influence as is well illustrated for the Amazon forest (Davidson et al., 2012) but also applies elsewhere. Since AR4, there is new evidence of more frequent severe drought episodes in the Amazon region that are associated with observed sea surface temperature increases in the tropical North Atlantic (*medium confidence*; Marengo et al., 2011a). There is *low confidence*, however, that these changes can be attributed to climate change (Section 4.3.3.1.3). There is *medium confidence* that tree mortality in the Amazon region has increased due to severe drought and increased forest fire occurrence and *low confidence* that this can be attributed to warming (Section 4.3.3.1.3, Figures 4-4, 4-8).

In freshwater ecosystems of most continents and climate zones, rising temperatures have been linked to shifts in invertebrate and fish community composition, especially in headwater streams where species are more sensitive to warming (Brown et al., 2007; Durance and Ormerod, 2007; Chessman, 2009; see also Section 4.3.3.3; *high confidence* in detection, *low confidence* in a major role of climate change due to numerous confounding factors). Long-term shifts in macroinvertebrate communities have been observed in European lakes where temperatures have increased (Burgmer et al., 2007).

18.3.3. Coastal Systems and Low-Lying Areas

Coastal systems are influenced by many anthropogenic and natural processes. Important climate-related drivers include changes in ocean temperature, salinity, and pH; and sea level (see Table 5-2). In coastal waters, both annual and seasonal changes in temperature tend to be larger than the average rate for the open ocean (Section 5.3.3). Sea surface temperatures have increased significantly during the past 30 years along more than 70% of the world's coastlines, with large spatial and seasonal variation, and the frequency of extreme temperature events in coastal waters has changed in many areas (Lima and Wethey, 2012). Seawater pH spans larger ranges and exhibits higher variability near coastlines, and anthropogenic ocean acidification can be enhanced or reduced by coastal geochemical processes (Borges and Gypens, 2010; Feely et al., 2010; Duarte et al., 2013, see also Box CC-OA).

While it is likely that extreme sea levels have increased globally since the 1970s, mainly as a result of mean sea level rise due in part to anthropogenic warming (WGI AR5 Sections 3.7.5-6, 10.4.3), local sea level trends are also influenced by factors such as regional variability in ocean and atmospheric circulation, subsidence, isostatic adjustment, coastal erosion, and coastal modification (see also Section 5.3.2). As a consequence, the detection of the impact of climate change in observed changes in relative sea level remains challenging (Nicholls et al., 2007, 2009; Menéndez and Woodworth, 2010). An exception is lower sea level in regions of isostatic rebound in response to reduced ice cover due to climate change (Kopp et al., 2010; Tamisiea and Mitrovica, 2011). In these regions, climate change has played a major role in the lowering sea level (*medium confidence*).

18.3.3.1. Shoreline Erosion and Other Coastal Processes

Throughout the world, the rate of shoreline erosion is increasing (Section 5.4.2.1). While processes related to climate change, such as rising mean sea levels (Leatherman et al., 2000; Ranasinghe and Stive, 2009), more frequent extreme sea levels (Woodworth et al., 2011), or permafrost degradation and sea ice retreat (Forbes, 2011) can be expected to enhance global erosion, there are multiple drivers involved in shoreline erosion that are unrelated to climate change including long shore sediment transport; the diversion of sediments by dams; and subsidence due to resource extraction, mining, and coastal engineering and development (see also Table 5-3). Owing to the fragmentary nature of the information available, and to the multiple natural and anthropogenic stressors contributing to coastal erosion, confidence in detection of a climate change contribution to observed shoreline changes is *very low*, with the exception of polar regions (Table 18-8; Mars and Houseknecht, 2007; Forbes, 2011).

Coastal lagoons and estuaries, as well as deltas, are highly susceptible to alterations of sediment input and accumulation (Syvitski et al., 2005; Ravens et al., 2009), processes that can be influenced by climate change via changes in mean and extreme sea levels, storminess, and precipitation. However, the primary drivers of widespread observed changes in those systems are human drivers other than climate change so that there is *very low confidence* in the detection of impacts related to climate change (Section 5.4.2).

Coastal aquifers are crucial for the water supply of densely populated coastal areas, in particular in small island environments and dry climates. Aquifer recharge is sensitive to changes in temperature and precipitation, and rising sea levels and saltwater overwash from storm surges can contribute to saline intrusion into groundwater (Post and Abarca, 2010; Terry and Falkland, 2010; White and Falkland, 2010; see also Section 29.3.2, Table 18-8). However, groundwater extraction for coastal settlements and agriculture is the main cause for widely observed groundwater degradation in coastal aquifers (e.g., White et al., 2007a; Barlow and Reichard, 2010). It is not yet possible to detect the impact of climate change on coastal aquifers with any degree of confidence (Rozell and Wong, 2010; White and Falkland, 2010).

Changes in water column mixing have combined with other factors such as nutrient loading to drive down oxygen concentrations and increase the number and extent of hypoxic zones (Vaquer-Sunyer and Duarte, 2011). These zones are characterized by very low oxygen and high CO_2 levels and, in some cases, exert strong local and regional effects on marine biota such as distribution shifts, habitat contraction or loss, and fish kills (Diaz and Rosenberg, 2008). The operation of other factors makes the detection of a climate change impact on the frequency, distribution, and intensity of hypoxia possible with only *medium confidence* and it is difficult to assess the relative magnitude of this impact (see Table 18-1).

18.3.3.2. Coastal Ecosystems

Coastal habitats and ecosystems experience cumulative impacts of land- and ocean-based anthropogenic stressors (Halpern et al., 2008). Most coral reefs, seagrass beds, mangroves, rocky reefs, and shelves have undergone substantial changes over the course of the last century. Fishing and other extractive activities, land use changes, and pollution have been responsible for a large proportion of these historical changes (Lotze et al., 2006). Biological responses to changes in the temperature, chemistry, and circulation of the ocean are complex and often interact with other anthropogenic factors.

Box 18-2 | Attribution of Mass Coral Bleaching Events to Climate Change

A critical source of energy for the maintenance and growth of coral is provided by symbiotic brown algae. Coral bleaching occurs when these symbionts leave their host. Bleaching events have deleterious impacts on corals and, depending on their severity and duration, can cause death. It is known that thermal stress can trigger coral bleaching (Muscatine, 1986; Hoegh-Guldberg and Smith, 1989; Jones et al., 1998). Mass bleaching events that affect entire reefs or coastal regions can occur when local or regional temperatures exceed the typical summer maximum for a period of a few weeks (Hoegh-Guldberg, 1999; Baker et al., 2008; Strong et al., 2011). The effect of elevated temperature is exacerbated by strong solar irradiance (Hoegh-Guldberg, 1999).

Since 1980, mass coral bleaching events have occurred throughout the tropics and subtropics at a rate without precedent in the literature (see also Boxes CC-CR and CC-OA, and Section 5.4.2.4). These events have often been followed by mass mortality (Hoegh-Guldberg, 1999; Baker et al., 2008). In the very warm year of 1998, for example, mass bleaching occurred in almost every part of the tropics and subtropics and resulted in the loss of a substantial fraction of the world's corals (Wilkinson et al., 1999). A large-scale bleaching event also occurred in the Caribbean during 2005 (Eakin et al., 2010).

Declining water quality, coastal development, increased fishing, and even tourism have also been implicated in the decline of coral communities over the past 50 years (Bryant et al., 1998; Gardner et al., 2003; Bruno and Selig, 2007; Sheppard et al., 2010; Burke et al., 2011; De'ath et al., 2012). However, given the scope of recent mass bleaching events, their co-occurrence with elevated temperatures, and a physiological understanding of the role of temperature in bleaching, there is *very high confidence* in the detection of the impact of climate change and *high confidence* in the finding that climate change has played a major role.

Coral reefs have been degraded due both to local anthropogenic factors such as fishing, land use changes, and pollution and to ocean warming related to climate change and also possibly to acidification (see Box CC-CR). Over the past 30 years, mass coral bleaching has been detected with *very high confidence* on all coasts, and warming is a major contributor (*high confidence*; for further discussion see Boxes 18-2, CC-OA).

Changes in abundance and distribution of rocky shore species have been observed since the late 1940s in the Northeast Atlantic (Hawkins et al., 2008), and the role of temperature has been demonstrated by experiments and modelling (Poloczanska et al., 2008; Wethey and Woodin, 2008; Peck et al., 2009; Somero, 2012; see also Section 5.4.2.2). Globally, the ranges of many rocky shore species have shifted up to 50 km per decade, much faster than most recorded shifts of terrestrial species (Helmuth et al., 2006; Poloczanska et al., 2013; see also Box 18-3). However, distinguishing the response of these communities to climate change from those due to other natural and anthropogenic causes is challenging. Weak warming, overriding effects of confounding factors, or biogeographic barriers can explain the fact that geographical distribution of some species did not change over the past decades (Helmuth et al., 2002, 2006; Rivadeneira and Fernández, 2005; Poloczanska et al., 2011).

Ocean warming has contributed to observed range shifts in vegetated coastal habitats such as coastal wetlands, mangrove forests and seagrass meadows (Section 5.4.2.3). Poleward expansion of mangrove forests, consistent with expected behavior under climate change, has been observed in the Gulf of Mexico (Perry and Mendelssohn, 2009; Comeaux et al., 2012; Raabe et al., 2012) and New Zealand (Stokes et al., 2010). High temperatures have impacted seagrass biomass in the Atlantic Ocean (Reusch et al., 2005; Díez et al., 2012; Lamela-Silvarrey et al., 2012), the Mediterranean Sea (Marbà and Duarte, 2010), and Australian waters (Rasheed and Unsworth, 2011). Extreme weather events also contributed to the overall degradation of seagrass meadows in a Portuguese estuary (Cardoso et al., 2008).

Decline in kelp populations attributed to ocean warming has occurred off the north coast of Spain (Fernández, 2011), as well as in southern Australia, where the poleward range expansion of some herbivores have also contributed to observed kelp decline (Ling, 2008; Ling et al., 2009a,b; Johnson et al., 2011; Wernberg et al., 2011a). The spread of subtropical invasive macroalgal species (e.g., Lima et al., 2007) may be adding to the stresses temperate seagrass meadows experience from ocean warming. Extreme temperature events can alter marine and coastal communities, as shown, for example, for the European 2003 heat wave (Garrabou et al., 2009), and the early 2011 heat wave off the Australian west coast (Wernberg et al., 2012).

In summary, there is *high confidence* in the detection of the impact of climate change on the abundance and distribution of a range of coastal species and *medium confidence* that climate change has played a major role in many cases. In specific cases, such as the decline of salt marshes and mangroves, the impact of climate change has been detected with *very low confidence* owing to the overriding effect of land use changes, pollution, and other factors unrelated to climate change.

18.3.3.3. Coastal Settlements and Infrastructure

Total damages from coastal flooding have increased globally over the last decades (*high confidence*); however, with exposure and subsidence constituting the major drivers, confidence in detection of a climate change impact is *very low* (Seneviratne et al., 2012, see also Sections 5.4.3.2, 5.4.4).

Recent global (e.g., Menéndez and Woodworth, 2010; Woodworth et al., 2011) and regional (e.g., Marcos et al., 2009; Haigh et al., 2010, 2011) studies have found increases in extreme sea levels consistent with mean sea level trends (see also Table 5-2), indicating that the increasing frequency of extreme water levels affecting coastal infrastructures observed so far is related to rising mean sea level rather than to changes in the behavior of severe storms. While vulnerability of coastal settlements and infrastructure to future climate change, in particular sea level rise and coastal flooding, is widely accepted and well documented (see Section 5.5), there is a shortage of studies discussing the role of climate change in observed impacts on coastal systems.

Increases in saltwater intrusion and flooding have been observed in low-lying agricultural areas of deltaic regions and small islands, but the contribution of climate change to this is not clear (e.g., Rahman et al., 2011; see also Sections 5.4.2.5, 5.4.3.3). While both climate change impacts on physiological and ecological properties of fish (e.g., Barange and Perry, 2009; see also Section 18.3.4) and vulnerability of coastal communities and fisherfolks to climate fluctuations and change (Badjeck et al., 2010; Cinner et al., 2012) are well established in the literature, there is *limited evidence* for observed effects of climate change on coastal fishery operations (see also Section 18.4.1.2).

18.3.4. Oceans

Since 1970, ocean temperatures have increased by around 0.1°C per decade in the upper 75 m and approximately 0.015°C per decade at 700 m (see Section 30.3.1.1). It is *very likely* that the increase in global ocean heat content observed in the upper 700 m since the 1970s has a substantial contribution from anthropogenic forcing (WGI AR5 Section 10.4.1).

The increased flux of CO_2 from the atmosphere to the ocean has reduced the average pH of sea water by about 0.1 pH units over the past century, with the greatest reduction occurring at high latitudes (see also Box CC-OA). These changes have been attributed to increases in the atmospheric concentration of greenhouse gases as result of human activities (*very high confidence*; WGI AR5 Section 10.4.4). Changes in wind speed, upwelling, water column stratification, surface salinity, ocean currents, and oxygen depth profile have also been been detected with at least *medium confidence* (WGI AR5 Chapter 3; Figures 30-5, 30-6).

Changes in the physical and chemical nature of ocean environments are predicted to have impacts on marine organisms and ecosystems, with many already having been observed across most ocean regions (Sections 6.2-3, 30.4-5). However, the detection of these predicted changes and the assessment of the role of climate change in them are complicated by the influence of long-term variability such as the Pacific Decadal Oscillation (PDO) and the Atlantic Multi-decadal Oscillation (AMO). The fragmentary nature of ocean observations and the influence of confounding factors such as fishing, habitat alteration, and pollution also represent significant challenges to detection and attribution (Hoegh-Guldberg et al., 2011; Parmesan et al., 2011; see also Box 18-3).

Table 18-1 | Observed changes in ocean system properties and their effects, with confidence levels for the detection of the effect of climate change and an assessment of the magnitude of its role.

Process	Confidence in		Role	Context	Reference
	Detection	Attribution			
Impacts of ocean acidification on pelagic marine biota	*Low*	*Very low*	Minor	For example, reduction in foraminiferan, coccolithophores, and pteropod shell weight. Attribution supported by experimental evidence and physiological knowledge.	1
Expansion of midwater hypoxic zones	*Medium*	*Low*	Minor	Oxygen minimum zones caused by enhanced stratification and bacterial respiration due to effects of warming	2
Regional and local impacts of expanding hypoxic zones	*Medium*	*Low*	Minor	Reduction of biodiversity, compression of oxygenated habitat for intolerant species, range expansion for tolerant taxa	3
Direct temperature effects on marine biota related to limited physiological tolerance ranges	*Very high*	*High*	Major	For example, large-scale latitudinal shifts of species distribution, changes in community composition; attribution supported by experimental and statistical evidence as well as physiological knowledge	4
Increase in net primary production at high latitudes	*Medium*	*Medium*	Major	At higher latitudes, net primary production is increasing owing to sea ice decline and warming. At the global scale, estimates vary regionally, and there is a discrepancy between satellite observations and open ocean time series sites.	5
Changes in microbial processes	*Low*	*Very low*	Minor	Limited understanding of microbial processes, drivers, and interactions, and subsequently of large-scale shifts in biogeochemical pathways such as oxygen production, carbon sequestration, and export production and nitrogen fixation	6

Key references and further related information for the assessment in this table:
[1]Wootton et al. (2008); De Moel et al. (2009); Moy et al. (2009); Bednaršek et al. (2012); Section 6.3.2; Box CC-OA
[2]Stramma et al. (2008); Stolper et al. (2010); Sections 6.1.1.3 and 6.3.3
[3]Levin et al. (2009); Ekau et al. (2010); Stramma et al. (2010, 2012); Sections 6.3.3, 6.3.5, and 30.5
[4]Merico et al. (2004); Perry et al. (2005); Pörtner and Farrell (2008); Beaugrand et al. (2010); Alheit et al. (2012); Section 6.3.1
[5]Behrenfeld et al. (2006); Saba et al. (2010); Arrigo and Van Dijken (2011); Section 6.3.4; Box CC-PP
[6]Sections 6.3.1.2, 6.3.2.2, 6.3.3.2, and 6.3.5.2

18.3.4.1. Impacts on Ocean System Properties and Marine Organisms and Ecosystems

Greater thermal stratification in many regions has reduced ocean ventilation and mixing depth. As this reduces the availability of inorganic nutrients, it can reduce primary productivity in surface layers. However, trends in primary production from different observational methods disagree (Sections 6.1.1, 6.3.4; Box CC-PP). Coastal upwelling has increased in some regions bringing greater concentrations of nutrients to surface waters, boosting productivity and enhancing fisheries output (see Section 30.5.5). Increases in productivity also occurred with warming and sea ice loss at high latitude (*medium confidence*; Table 18-1).

Poleward shifts in the distributions of zooplankton, fish, seabirds, and benthic invertebrates related to climate change have been detected with *high confidence* in the well-studied Northeast Atlantic. There is also *high confidence* that climate change has played a *major role* in these shifts (Box 6-1; Sections 6.3, 30.5.1). In many regions, temperature exerts the strongest influence on ecosystems and the responses of ecological systems to changing temperature are well studied. However, it is often difficult to clearly identify the interaction of temperature with other factors (Section 6.3.5). Some studies have found changes in the abundance of fish species that are consistent with regional warming, with differences in response between species, in line with differential specializations of coexisting species (Sections 6.2, 6.3.1; see also Pörtner, 2012). Anthropogenic influences modulate responses to climate, for example, due to exploitation status (Tasker, 2008; Belkin, 2009; Overland et al., 2010; Schwing et al., 2010), with more heavily exploited species being more sensitive to environmental variability in general, including temperature trends and extremes (Hsieh et al., 2005, 2008; Stige et al., 2006).

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Laboratory experiments have shown that a broad range of marine organisms (e.g., corals, fish, pteropods, coccolithophores, and macroalgae), physiological processes (e.g., skeleton formation, gas exchange, reproduction, growth, and neural function), and ecosystems processes (e.g., productivity, reef building, and erosion) are sensitive to changes in pH and carbonate chemistry of seawater (Section 6.2, Box CC-OA). However, few field studies have been able to detect specific changes in marine ecosystems to ocean acidification owing to the inability to identify the effect of ocean acidification from ocean warming or local factors (Wootton et al., 2008; De Moel et al., 2009; Moy et al., 2009; Bednaršek et al., 2012; see also Section 6.3.2).

There has been a substantial increase in the number of studies documenting significant changes in marine species and processes since the AR4. A new meta-analysis using a database of long-term observations from peer-reviewed studies of biological systems, with nearly half of the time series extending prior to 1960, shows that more than 80% of observed responses are consistent with regional climate change (see Section 30.4, Box CC-MB). Poloczanska et al. (2013) argue that the high consistency of marine species' responses across geographic regions (coastal to open ocean, polar to tropical), taxonomic groups (phytoplankton to top predators), and types of responses (distribution, phenology, abundance) reported in their analysis support the detection of a widespread impact of climate change on marine populations and ecosystems (see Sections 30.4 and 30.5 for more detail). Table 18-2 gives examples of the manifestation of climate change on marine species and ecosystems.

18.3.4.2. Observed Climate Change Effects across Ocean Regions

Climate change has affected physical properties across the ocean, with regional variations (Table 30-1; Figures 30-2 to 30-5; WGI AR5 Chapter 3). Confidence in the detection and attribution of these impacts also varies regionally, reflecting differences in system understanding, data availability, influence of long-term natural variability, and the impact of factors unrelated to climate change. The attribution of changes in heat content to climate change is less certain regionally than globally, but warming has been detected with *high confidence* in all basins except

Table 18-2 | Observed changes in marine species and ecosystems, with confidence levels for the detection of the effect of climate change and an assessment of the magnitude of its role (see also Sections 6.2, 6.3, and 30.4; Box CC-MB).

Process	Confidence in		Role	Context	Reference
	Detection	Attribution			
Range shifts of fish and macroalgae	*High*	*High*	Major	Changes in species biogeographical ranges to higher latitudes or greater depths	1
Changes in community composition	*High*	*High*	Major	Due to effects of warming, hypoxia, and sea ice retreat	1
Changes in abundance	*High*	*Medium*	Major	Observed in fish, corals, and intertidal species	1
Impacts on large non-fish species, e.g., walruses, penguins, and other sea birds	*High*	*High*	Major	Observed effects include changing abundance, phenology, species distribution and turtle sex ratios, and are mediated mostly through changes in resource availability, including prey.	2
Impacts on reef-building corals	*Very high*	*High*	Major	Effects attributed mostly to warming and rising extreme temperatures, though ocean acidification may contribute	3
Changes in fish species richness in temperate and high-latitude zones	*High*	*Medium*	Major	Effect associated with loss of sea ice and latitudinal species shifts due to warming trends	4

Key references and further related information for the assessment in this table:
[1]Müller et al. (2009); Stige et al. (2010); Sections 6.3.1 and 30.4; Box CC-MB
[2]Grémillet and Boulinier (2009); McIntyre et al. (2011); Section 6.3.7
[3]Hoegh-Guldberg (1999); Hoegh-Guldberg et al. (2007); Baker et al. (2008); Veron et al. (2009); Sections 6.3.1.4 and 6.3.1.5; Box CC-CR
[4]Hiddink and ter Hofstede, (2008); Beaugrand et al. (2010); Box 6-1; Section 6.3.1.5

Box 18-3 | Differences in Detection and Attribution of Ecosystem Change on Land and in the Ocean

Marine and terrestrial ecosystems differ in fundamental ways. Gradients in turbulence, light, pressure, and nutrients uniquely drive fundamental characteristics of organisms and ecosystems in the ocean. While the critical factor for transporting nutrients to marine primary producers is ocean mixing driven by wind, water is the primary mode for transporting nutrients to land plants. In addition to these characteristics, marine ecosystems are often more technically difficult and costly to explore than terrestrial equivalents, which explains the low number and shorter scientific studies of marine ecosystems (Hoegh-Guldberg and Bruno, 2010). The latter has restricted the extent to which changes within the ocean can be detected and attributed.

Impacts of climate change in terrestrial and marine systems differ significantly for the same types of measures, for example, species phenology and range shifts, leading to differences in experts' interpretations of the data and possibly divergent levels of confidence in detection and attribution. There are also fundamental differences in exposure of organisms to recent warming, their biological responses, and our ability to detect change through observations. Changes in temperature of ocean systems have generally been less than those of terrestrial ecosystems over the last 4 decades (Burrows et al., 2011). Furthermore, despite higher variability the horizontal spatial gradient of temperature change (°C km^{-1}) is generally much higher in terrestrial ecosystems than in marine ecosystems. All else being equal, the net result is that species have generally needed to move much shorter distances in terrestrial ecosystems to stay within their preferred climates, also due to the influence of the topography such as mountain ranges (Burrows et al., 2011), although many marine species can potentially exploit strong vertical thermal gradients to attenuate the need for range shifts in response to warming.

Species and ecosystems may respond very differently to these climate signals in ways that influence the ability to detect change. For example, a comparison of ectotherm species (i.e., species that do not actively regulate their body temperatures, such as reptiles and fish) indicates that marine species' ranges have tracked recent warming at both their poleward and equatorial range limits, while many terrestrial species' ranges have tracked warming only at their poleward range limits (Sunday et al., 2012). Biological processes influencing phenological shifts may also differ substantially between systems. For example, the effect of climate on the timing of flowering of terrestrial plants at high latitudes is only moderately influenced by confounding effects, whereas the timing of phytoplankton blooms in high-latitude marine systems is highly dependent on ocean temperature and associated stratification and changes in nutrient availability.

Eastern boundary upwelling systems (Table 30-1, Figure 30-2). Recent research shows declining oxygen levels (*medium confidence*; Section 30.3.2.3) and deep penetration of warming in some regions. Regional estimates of CO_2 uptake are in line with global estimates, and ocean acidification has been detected with *high confidence* in most regions (Section 30.3.2.2; WGI AR5 Section 3.8.2).

The high latitude spring bloom systems of the NH show strong warming and associated effects (see above). In the North Pacific, the Bering Sea has undergone major changes in recent decades as a result of climate variability, climate change, and fishing impacts (Litzow et al., 2008; Mueter and Litzow, 2008; Jin et al., 2009; Hunt et al., 2010). Loss of sea ice has led to the retreat of the cold pool in parts of the Bering Sea, and northward expansion of productivity (Wang et al., 2006; Mueter and Lizow, 2008; Brown and Arrigo 2012; see also Section 30.5.1.1.2).

Marginal seas such as the East China Sea are also warming rapidly, with subsequent impacts such as declining primary productivity and fisheries yields as well as other ecological changes (Section 30.5.4.1). However, other human pressures including over-fishing, habitat alteration, and nutrient loading are important contributing factors and it is difficult to disentangle these from the impacts of climate change.

Semi-enclosed seas such as the Black and Baltic Seas and the Arabian/Persian Gulf show differing patterns of change over the past decades (Section 30.5.3.1). Expansions of hypoxic zones in the Baltic and Black Seas have been detected. Although there is *high confidence* that climate change has had a role, its magnitude is difficult to assess in light of other contributing factors. Coral reefs in the Arabian/Persian Gulf and Red Sea have experienced widespread bleaching in 1996 and 1998 associated with elevated temperature with *high confidence* that climate change has played a major role.

Warming of the Mediterranean has been associated with mass mortality events as well as invasions and spread of new warm water species, resulting in the "tropicalization" of fauna with *high confidence* in a major role for climate change (Section 30.5.3.1.5). In many tropical regions and the subtropical gyres of the Pacific, Indian, and Atlantic, periodic heat stress related to climate change has combined with other local stresses to cause mass coral bleaching and mortality (see also Box CC-CR, Section 30.5).

In other regions, such as the California Current upwelling system, there is *very high confidence* in both the detection and attribution of ecological changes associated with climate change, but separating the effects of El Niño-Southern Oscillation (ENSO) and the PDO from those of anthropogenic climate change is not possible.

In overall terms, attributing observed local and regional changes in marine species and ecosystems to climate change remains an important question for ongoing research (Stock et al., 2010).

18.4. Detection and Attribution of Observed Climate Change Impacts in Human and Managed Systems

Observed impacts on human systems have received considerably less attention in previous IPCC reports and the scientific literature, compared to observed impacts on natural systems. Human systems' "normal state in the absence of climate change" is almost never stationary. Confounders other than climate change have been and continue to drive the normal evolution of these systems, with climate often playing a relatively minor role. Further, monitoring in many of the systems has been and continues to be inadequate. It is therefore difficult to detect and attribute the signal of climate change in the majority of human systems, food production systems constituting one noteworthy exception. There is emerging literature estimating the sensitivity to climate of many sectors within the human system (see Box 18-4), yet climate impacts are often not detectable over the impacts from non-climate confounders.

For some human systems, the clearest situations where a climate signal had a detectable and sometimes attributable impact are during extreme weather events. Impacts of extreme events and single event attribution are therefore discussed in Section 18.4.3, and the discussion is expanded to include responses to extreme weather for some sectors. Overall, the literature has made significant progress for certain sectors, such as food systems, since AR4. The following sections provide a synthesis of findings with regard to food systems, economic systems, human health, human security, and human livelihoods and poverty, which are documented in greater detail in Chapters 7, 9, 10, 11, 12, and 13. They also incorporate evidence from regional chapters and further available literature, especially for the discussion of extreme events, human security, and observed changes in indigenous communities.

18.4.1. Food Production Systems

Detection and attribution of climate change impacts in food systems is challenging, given that the behavior of the system in the absence of climate change is driven by a large number of other factors (Section 7.2.1). For cropping systems, these confounders include, but are not limited to, cultivar improvement and increased use of synthetic fertilizers, herbicides, and irrigation. These confounders are often not well measured in terms of their distribution across space and time. Further, it is difficult to quantify or model the exact relationship between these confounders and outcomes of interest (e.g., crop yield or pasture productivity). In addition, the role of farmers' behavior in response to climate change requires significant assumptions and has been shown to change over time (Section 7.2.1). The discussion below is limited to crop systems and fisheries, as literature is scarce on observed impacts for other important sources of food.

18.4.1.1. Agricultural Crops

A significant number of studies have provided impact estimates of observed changes in climate on cropping systems over the past few decades (e.g., Auffhammer et al., 2006; Kucharik and Serbin, 2008; Ludwig et al., 2009; Lobell et al., 2011; Tao et al., 2012; see also Figure 7-2). Over the past several decades, observed climate trends have adversely affected wheat and maize production for many regions, as well as the total global production of these crops (*medium confidence* in a minor role of climate change in overall production). Climate change impacts on rice and soybean yields over this time period have been small in major production regions and globally (*medium confidence*; Figure 7-2). In some high-latitude regions, such as the UK and northeast China, warming has benefitted crop production during recent decades (*high confidence* in a minor role of climate change; Section 7.2.1.1; Jaggard et al., 2007; Chen. C. et al., 2011). At the continental or global scale, observed trends in some climatic variables, including mean summer temperatures, attributed to anthropogenic activity (see Section 7.2.1.1; WGI AR5 Section 10.3.1 and Table 10-1) have had significant negative impacts on trends in yields for certain crops (Lobell and Field, 2007; You et al., 2009; Lobell et al., 2011).

Attributable trends have been found not only in the seasonal averages of climate variables, but also for extremes (WGI AR5 Section 10.6). Extreme rainfall events are widely recognized as important to cropping systems (Rosenzweig et al., 2002), and global scale changes in the patterns of rainfall extremes have been attributed to anthropogenic activity (Min et al., 2011). High nighttime temperatures are harmful to most crops, particularly for rice yield (Peng et al., 2004; Wassmann et al., 2009; Welch et al., 2010) and quality (Okada et al., 2009). Daytime extreme heat is also damaging and sometimes lethal to crops (Porter and Gawith, 1999; Schlenker and Roberts, 2009). At the global scale, trends in annual maximum daytime temperatures have been attributed to greenhouse gas emissions (Christidis et al., 2011; Zwiers et al., 2011), and similar observations have been made for the occurrence of very hot nights (WGI AR5 Section 10.6.1.1; Seneviratne et al., 2012).

Changing atmospheric conditions are affecting crops both positively and negatively. It is *virtually certain* that the increase in atmospheric CO_2 concentrations since preindustrial times has improved water use efficiency and yields most notably in C_3 crops. These effects are however of relatively minor importance when explaining total yield trends (Amthor, 2001; McGrath and Lobell, 2011). Emissions of CO_2 have been associated with tropospheric ozone (O_3) precursors (Morgan et al., 2006;

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Box 18-4 | The Role of Sensitivity to Climate and Adaptation for Impact Models in Human Systems

Impacts of climate change on a measurable attribute of a human system occur only if (1) the attribute is sensitive to climate and (2) a change in climate has occurred. Many studies now attempt to quantify both climate sensitivity of various systems and observed changes in climate.

Assessment of the sensitivity of an outcome such as crop yields, heat-related mortality, or migration to climate relies on observed climate variability either across space (e.g., Schlenker et al., 2005), time (e.g., Mann and Emanuel, 2012), or space and time (e.g., Dell et al., 2012). Though there are many studies using climate variability across space, the lack of long observational weather time series required for exploring climate variability across space and time have limited the opportunities for study. A number of studies have instead estimated the sensitivity of outcomes to short-run fluctuations (e.g., weather) in order to project the future impacts of climate change (Deschênes and Greenstone, 2007, 2011), or attribute impacts for the past (Auffhammer et al., 2006). The issue with impact studies using a weather-based sensitivity measure is that they cannot provide estimates of impacts based on the sensitivity to climate. For example, farmers may respond to an unusually hot summer, which is a weather event, by applying more irrigation water. However, in the long run farmers may respond to a warmer climate by switching crops, changing irrigation technology, or abandoning farming altogether. The two sensitivities and resulting magnitudes of attributable impacts due to a change in weather versus a change in climate are therefore different. To detect and attribute a change in a system to climate change, one needs to combine a measure of sensitivity of the outcome to climate with climate observations under climate change.

Mills et al., 2007; see also Section 7.3.2.1.2). O_3 suppresses global output of major crops, with reductions estimated at roughly 10% for wheat and soy and 3 to 5% for maize and rice (Van Dingenen et al., 2009). Detected impacts are most significant for India and China, but can also be found for soybean and maize production in the USA in recent decades (Fishman et al., 2010).

18.4.1.2. Fisheries

Many new studies focus on the relationship between the dynamics of marine fish stocks and climate, suggesting a sensitivity to climate of these stocks and on the fisheries that exploit them (Hollowed et al., 2001; Roessig et al., 2004; Shriver et al., 2006; Brander, 2007). Some fisheries and aquaculture do not show evidence of climate change impacts (e.g., aquaculture in the UK and Ireland; Callaway et al., 2012), while many others do with both positive and negative changes (see also Sections 7.2.1.1, 18.3.4, 30.6.2.1).

There is *high confidence* in the detection of a climate change impact on the spatial distributions of marine fishes (Perry et al., 2005) and in the timing of events like spawning and migration (Sydeman and Bograd, 2009), with *high confidence* of a major role of climate change (see Sections 18.3.4, 30.4; Box CC-MB). This distributional shift is reflected in the species composition of harvest, with the relative share of warm water species increasing (Cheung et al., 2013). The impacts of ocean warming and acidification on fish stocks vary from region to region (Section 30.6.2.1). To date, the role of climate change in change in fish stocks and fishery yields is, in most cases, minor (*high confidence*) in relation to other factors such as harvesting, habitat modification, technological development, and pollution (Brander, 2010).

18.4.2. Economic Impacts, Key Economic Sectors, and Services

18.4.2.1. Economic Growth

In low-income countries, careful tracking of incomes and temperatures over an extended period, taking into account important confounders, shows that higher annual temperatures as well as higher temperatures averaged over 15-year periods result in substantially lower economic growth (Dell et al., 2012). This effect is not limited to the level of per capita income, but also to its rate of growth. Declining rainfall over the 20th century partly explains the slower growth of sub-Saharan economies relative to those of other developing regions (Barrios et al., 2006; Brown et al., 2011). Dell et al. (2009) find that 1°C of warming reduces income by 1.2% in the short run and by 0.5% in the long run. The difference is argued to be due to adaptation. Horowitz (2009) finds a much larger effect: a 3.8% drop in income in the long run for 1°C of warming. One proposed mechanism for this is the impact of heat stress on workers in the workplace (Dash and Kjellström, 2011; Dunne et al., 2013). Temperature shocks have negatively affected the growth of developing countries' exports, for which 1°C of warming in a given year reduced the growth rate of its exports by 2.0 to 5.7 percentage points (Jones and Olken, 2010). The export sectors most affected are agricultural and light manufacturing exports.

18.4.2.2. Energy Systems

Energy production and consumption is growing rapidly globally, with much of the growth taking place in low-income and emerging economies. Various parts of the energy sector are known to be sensitive to climate change (cf. Ebinger and Vegara, 2011). Higher temperatures raise the demand for cooling and lower the demand for heating. Cooling demand is largest in the summer and in some areas peak loads during the summer months have increased, this peak being highly correlated with summer maximum temperatures (Franco and Sanstad, 2008). There are also opposing effects of warmer winters and summers on electricity and gas demand. Statistical studies have confirmed this U-shaped relationship of energy and electricity demand in temperature for the USA and elsewhere (Isaac and van Vuuren, 2009; Akpinar-Ferrand and Singh, 2010; Deschênes and Greenstone, 2011).

On the supply side, sensitivity to climatic factors such as ambient temperature, wind speeds, or snow and ice is well known for many energy technologies and part of the transmission infrastructure (see Sections 10.2.2-3); however, there are no studies available that discuss observed effects of climate change on the energy sector.

18.4.2.3. Tourism

Tourism is a climate sensitive economic sector and ample research has been performed to understand its sensitivity to climate change and impacts of (future) climate change on tourism, yet few studies have focused on detection and attribution of observed impacts (cf. Scott et al., 2008; see also Section 10.6).

A comparatively well-studied area is the sensitivity of the winter sports industry in lower lying areas to climate. For example, the increase in investment in artificial snow machines in the European Alps can be attributed with *high confidence* to a general decrease of snow depth, snow cover duration, and snowfall days since the end of the 1980s for low-elevation mountain stations (Durand et al., 2009; Valt and Cianfarra, 2010; Voigt et al., 2011), which in turn has been attributed to anomalous higher winter temperatures over the past 20 years (Marty, 2008).

Variability in precipitation, shrinking glaciers, and milder winters has been shown to negatively affect visitor numbers in winter sports areas in Europe and North America (Becken and Hay, 2007). Another indirect effect of climate change that has been reported is a rise in popularity of destinations that are perceived to be at risk from climate change (e.g., Eijgelaar et al. (2010) for Antarctic glaciers, or Farbotko (2010) for Tuvalu).

18.4.3. Impacts of Extreme Weather Events

The impacts of extreme weather events depend on the frequency and intensity of the events, as well as exposure and vulnerability of society and assets. The last several decades have seen changes in the frequency and intensity of extreme weather events including extreme temperature, droughts, heavy rainfall, and tropical and extratropical cyclones with *low* to *very high confidence*, depending on the type of extreme event (IPCC, 2012; WGI AR5 Chapter 2). However, the impacts of extreme weather events also depend on the vulnerability and exposure of systems. It is possible that climate change can affect vulnerability and exposure, but typically both are influenced primarily by non-climate confounders, most notably economic development.

18.4.3.1. Economic Losses Due to Extreme Weather Events

Extreme weather events can result in economic impacts related to damage to private and public assets as well as the temporary disruption of economic and social activities, long-term impacts, and impacts beyond the areas affected. Some economic and especially social impacts are not readily monetizable and are thus excluded from most economic assessments (Handmer et al., 2012, their Sections 4.5.1, 4.5.3).

Economic costs of extreme weather events have increased over the period 1960–2000 (*high confidence*), with insured losses increasing more rapidly than overall losses (Section 10.7.3; Handmer et al., 2012, their Sections 4.5.3.3, 4.5.4.1). This is also reflected by an increase in the frequency of extreme weather-related disasters over the same period (Neumayer and Barthel, 2011). Recent studies from Mexico and Colombia highlight both variability and positive trends in disaster frequency (unadjusted) losses and other damage metrics (Saldaña-Zorrilla and Sandberg, 2009; Marulanda et al., 2010; Rodriguez-Oreggia et al., 2013). However, the greatest contributor to increased cost is rising exposure associated with population growth and growing value of assets (*high confidence*; Bouwer et al., 2007; Bouwer, 2011; Barthel and Neumayer, 2012; Handmer et al., 2012, their Sections 4.2.2, 4.5.3.3, Box 4-2). To account for changes over time in the value of exposed assets, many studies attempt to normalize monetary losses by an overall measure of changes in asset value. A majority of studies have found no detectable trend in normalized losses (Bouwer, 2011). Studies on insured losses that in general meet higher data quality standards than data on overall losses due to thoroughly monitored payouts have focused on developed countries including Australia, Germany, Spain, the USA (Changnon, 2007, 2008, 2009a,b; Barredo et al., 2012; Barthel and Neumayer, 2012; Sander et al., 2013; see also Section 10.7.3). Studies of normalized losses from extreme winds associated with hurricanes in the USA (Miller et al., 2008; Pielke Jr. et al., 2008; Schmidt et al., 2010; Bouwer and Botzen, 2011) and the Caribbean (Pielke Jr. et al., 2003), tornadoes in the USA (Brooks and Doswell, 2002; Boruff et al., 2003; Simmons et al., 2013), and wind storms in Europe (Barredo, 2010) have failed to detect trends consistent with anthropogenic climate change, although some studies were able to find signals in loss records related to climate variability, such as damage and loss of life due to wildfires in Australia related to ENSO and Indian Ocean dipole phenomena (Crompton et al., 2010), or typhoon loss variability in the western North Pacific (Welker and Faust, 2013). Effects of adaptation measures (disaster risk prevention) on disaster loss changes over time cannot be excluded as research is currently not able to control for this factor (Neumayer and Barthel, 2011).

In conclusion, although there is *limited evidence* of a trend in the economic impacts of extreme weather events that is consistent with a change driven by observed climate change, climate change cannot be excluded as at least one of the drivers involved in changes of normalized losses over time in some regions and for some hazards.

18.4.3.2. Detection and Attribution of the Impacts of Single Extreme Weather Events to Climate Change

Although most studies on the relationship between climate change and extreme weather events have focused on changes over time in their

Table 18-3 | Illustrative selection of recent disasters related to extreme weather events, with description of the impact event, the associated climate hazard, recent climate trends relating to the weather event, and recent trends relating to the consequences of such a weather event.

Date and locale	Impact event	Associated climate hazard	Trends relating to likelihood of climate hazard	Trends relating to consequence of climate hazard
France, summer 2003	Approximately 15,000 excess deaths (Hémon and Jougla, 2003; Fouillet et al., 2006)	Record hot days/heat wave (Hémon and Jougla, 2003; Fouillet et al., 2006)	Increasingly frequent hot days and heat waves in recent decades (Perkins et al., 2012; Seneviratne et al., 2012) (*high confidence*)	• Aging population, increasing population, trends in marital status (Hémon and Jougla, 2003; Prioux, 2005; Fouillet et al., 2006; Rey et al., 2007) • Difficulties staffing health services, undeveloped early warning system (Lalande et al., 2003; Fouillet et al., 2008)
Atlantic and Gulf coasts of the United States, 2005	More than 1,000 deaths and more than US$100 billion in damage (Beven et al., 2008)	Record number of tropical storms, hurricanes, and category 5 hurricanes (Bell et al., 2006)	Recent increase in frequency but no clear century-scale trends in USA landfalling tropical storms or hurricanes (WGI AR5 Section 2.6.3, Knutson et al., 2010) (*high confidence*)	• More population, settlement, and wealth in coastal areas (Pielke Jr. et al., 2008; Schmidt et al., 2010) • Strengthening of building codes (IntraRisk, 2002)
Mozambique, early 2007	More than 100,000 people displaced by flooding (Foley, 2007; Artur and Hilhorst, 2012)	High rainfall in upper Zambezi Basin in preceding months; passage of Cyclone Favio (Thiaw et al., 2008)	Warming and decreasing rainfall leading to lower discharge of the Zambezi (Dai et al., 2009) (*low confidence*) Decreasing frequency of tropical cyclones in the Mozambique Channel during past 50 years (Mavume et al., 2009) (*medium confidence*)	• Increased settlement of Zambezi flood plain following dam construction (Foley, 2007) • Development of emergency response plans (Cosgrave et al., 2007; Foley, 2007)
Colombia, October–December 2010	Floods affecting 4 million people; US$7.8 billion total damage (Hoyos, N. et al., 2013)	Wettest year since records began 40 years ago (Martinez et al., 2011)	No clear trend in discharge of rivers in flood-affected areas since 1940 (Hoyos, N. et al., 2013) (*low confidence*)	• Rapid urbanization, with high concentration of residential areas in flood-prone areas (OSSO, 2013; Álvarez-Berríos et al., 2013) • Increasing vulnerability of rural population over the past decades and highly fragile urban systems (e.g., water and gas) (OSSO, 2013)
Pakistan, July–September 2010	Flooding leading to 2,000 deaths; 20 million affected; total loss US$10 billion (NDMA, 2011)	Exceptionally high monsoon rainfall over northern Pakistan during July and August (Houze Jr. et al., 2011; Rajeevan et al., 2011; Webster et al., 2011)	No substantial trend in heavy rainfall event frequency in northern Pakistan in past several decades (Wang, S.-Y. et al., 2011; Webster et al., 2011) (*low confidence*)	• Rapid population growth and expansion of formal and informal human settlements (Oxley, 2011) • Decreased risk through development of flood and disease warning systems and disaster planning (NDMA, 2011) • Increased risk from deforestation on mountainous slopes (Ali et al., 2006) • Recent unrest in north constrains ability of institutions to deliver basic services (World Bank and ADB, 2010)
European Russia, July–August 2010	Burned area >12,500 km (Müller, 2011)	Record hot days (Barriopedro et al., 2011; Müller, 2011) Unusually dry June–August (Bulygina et al., 2011)	Trends in temperature, precipitation, humidity, soil moisture, and snow cover toward less conducive climatic conditions for fire (Groisman et al., 2007) (*medium confidence*)	• Increased risk from draining of peat bogs in 1960s and earlier (Global Fire Monitoring Center, 2010; Müller, 2011) • Increased risk from poorly implemented devolution of forest management and forest fire protection in 2007 to regional administrations (Global Fire Monitoring Center, 2010)
Russia, summer 2010	Grain harvest 30% lower than forecast (Wegren, 2011)	Hottest June–August in at least 130 years, unusually dry June–August (Bulygina et al., 2011)	~1°C summer warming trend over last 70 years (Gruza and Mescherskaya, 2008; Bulygina et al., 2011) (*very high confidence*)	• Increase in grain production partially due to government support programs (Wegren, 2011)
Southeast Queensland, Australia, January 2011	Floods affecting >200,000 people; >30,000 homes flooded; damages and cost to economy of US$2.5–10 billion (Hayes and Goonetilleke, 2012)	2010 was the wettest year since 1974, with landfall of tropical cyclone in December and wet start to January resulting in highest flood since 1974 (Van den Honert and McAneney, 2011; Hayes and Goonetilleke, 2012).	Decreasing frequency of intense floods since 1840 (Van den Honert and McAneney, 2011) (*medium confidence*)	• Increased development in flood-prone urban areas (Van den Honert and McAneney, 2011) • Lack of development of riverine flood insurance (Van den Honert and McAneney, 2011; Ma et al., 2012)
Thailand, 2011	Prolonged inundation of urban and industrialized areas; manufacturing losses of about US$32 billion (World Bank, 2012)	One of the wettest monsoon seasons on record in middle and upper Chao Phraya Basin, resulting in flooding (Komori et al., 2012; Van Oldenborgh et al., 2012)	No detectable change in precipitation over the basin (Van Oldenborgh et al., 2012) (*low confidence*)	• Economic development focused on large industrial estates built in flood plains (Chongvilaivan, 2012; Courbage et al., 2012) • Recent spell of political instability (Courbage et al., 2012) • Subsidence from groundwater pumping (Phien-Wej et al., 2006)
Contiguous United States, summer 2012	Agricultural drought, with 57% of cropland and 43% of farms experiencing at least severe drought (Crutchfield, 2013)	Second warmest summer and warmest month (July) in the contiguous USA, and one of the driest March–July periods in the central USA in the 118-year record (Crouch et al., 2013; Kumar et al., 2013)	~0.5°C warming in summer over the last century (Menne et al., 2009) (*very high confidence*) No substantial long-term trend in drought occurrence (Peterson et al., 2013) (*medium confidence*)	Significant growth in area dedicated to soy and maize (FAOSTAT, 2013)

frequency and intensity, a few studies have focused on the contribution of climate change to specific events (WGI AR5 Section 10.6.2). Assessing the contribution of climate change to a specific event poses particular challenges, both in terms of methodology and communication of results (Allen, 2011; Curry, 2011; Hulme et al., 2011; Trenberth, 2011). Only a few studies have attempted to evaluate the role of climate change in the impacts of individual extreme weather events. For instance, Pall et al. (2011) and Kay et al. (2011), using observational constraints on climate and hydrologic model simulations, concluded that greenhouse gas emissions have increased the probability of occurrence of a comparable flooding event in autumn 2000 over the UK.

In highly temperature-sensitive regions, such as high mountains, several extreme impact events of recent decades can be qualitatively attributed to effects of long-term warming (*high confidence*), namely glacier lake outburst floods due to glacier recession and subsequent formation of unstable lakes (Evans and Clague, 1994; Carey, 2005; Bajracharya and Mool, 2009), debris flows from recently deglaciated areas, and rock fall and avalanches following the loss of mechanical support accompanying glacier retreat (Haeberli and Beniston, 1998; Oppikofer et al., 2008; Huggel et al., 2012b; Stoffel and Huggel, 2012; see also Section 18.3.1.3). Multi-step approaches can be used to evaluate the contributions of anthropogenic emissions to recent damaging extreme events (Hegerl et al., 2010).

Irrespective of whether a specific event can be attributed in part to climate change, there is ample evidence of the severity of related impacts on people and various assets. Both low- and high-income countries have been strongly impacted by extreme weather events in recent years, but the impacts relative to economic strength have been higher in low-income countries (Handmer et al., 2012). Similarly, at the national scale, poor or elderly people have been disproportionately affected, as documented for Hurricane Katrina in the USA in 2005 (Elliott and Pais, 2006; Bullard and Wright, 2010) or the 2003 European heat wave (Fouillet et al., 2008). Exacerbating effects of extreme weather events are mostly of non-climatic nature, including increasing exposure and urbanization, land use changes including deforestation, or vulnerable infrastructure. Table 18-3 lists a selection of recent weather-related disasters, and lists various factors contributing to long-term changes in the risk of damage, including recent climate change.

18.4.4. Human Health

IPCC AR4 (Confalonieri et al., 2007) concluded that there was *weak* to *moderate evidence* of effects of recent observed climate change on three main categories of health exposure (ranging from *low* to *medium confidence*): vectors of human infectious diseases (changes in distribution), allergenic pollen (changes in phenology), and extreme heat exposures (trend in increased frequency of very hot days and heat wave events). Overall, there was a lack of evidence for observed effects of climate change on human health outcomes, and this generally remains the case (see Chapter 11). Evaluation of the detection and attribution of impacts on health outcomes requires disentangling the roles of changes in exposures (e.g. patterns), control measures (e.g., vaccination, drug resistance), population structures (e.g., population aging), and reporting practices.

The most direct potential health impact of climate change is through exposure to higher temperatures, as the association between very hot days and increases in mortality is very robust (Section 11.4.1). Recent decades have seen a shift toward more frequent hot extremes and less frequent cold extremes (*high confidence*; Seneviratne et al., 2012; WGI AR5 Table 2.13). However, the translation of this trend in hazard to a trend in exposure is complicated by changes in social, environmental, and behavioral factors (e.g., Carson et al., 2006; see also Table 18-3) and interseasonal mortality relationships (Rocklöv et al., 2009; Ha et al., 2011). Climate change has contributed to a shift from cold-related mortality to heat-related mortality during recent decades in Australia (*medium confidence*; Bennett et al., 2013). In a similar shift in England and Wales, a contribution from anthropogenic climate change has been detected (*medium confidence*; Christidis et al., 2010).

For pollen production, changes in phenology have been consistently observed in mid- to high latitudes with, for example, earlier onset in Finland (e.g., Yli-Panula et al., 2009) and Spain (D'Amato et al., 2007; García-Mozo et al., 2010; see also Section 4.3) over the past few decades. In North America, the pollen season of ragweed (*Ambrosia* spp.) has been extended by 13 to 27 days since 1995 at latitudes above 44°N (Ziska et al., 2011). Allergic sensitization of humans has changed over a 25-year period in Italy, but the attribution to observed warming remains unclear (Ariano et al., 2010).

There is *limited evidence* regarding the role of observed warming in changes in tick-borne disease in mid- to high latitudes. While patterns of changes in tick-borne encephalitis (TBE) incidence in the Czech Republic match those expected from observed warming (Kriz et al., 2012), the upsurge of TBE in the 1980–1990s in Central and Eastern Europe generally has been attributed to socioeconomic factors (human behavior) rather than temperature (Šumilo et al., 2008, 2009). Changes in the latitudinal and altitudinal distribution of ticks in Europe and North America are consistent with observed warming trends (e.g., Gray et al., 2009; Ogden et al., 2010), but there is no evidence so far of any associated changes in the distribution of human cases of tick-borne diseases. There is *limited evidence* of a change in the distribution of rodent-borne infections in the USA (plague and tularemia) consistent with observed warming (Nakazawa et al., 2007). Specifically, a northward shift of the southern edge of the distributions of the diseases (based on human case data for period 1965–2003) was observed. There was no change detected in the northern edge of the distributions, however.

Globally, the dominant trend concerning malaria has been a contraction of the geographical range and a decrease in endemicity over the past century due to changes in land cover, behavior, and health care (Gething et al., 2010). Given that the mosquito vector is climate sensitive, however, there may be specific locations where climate change matches the influence of these other factors. In the Kericho region of Kenya, both increasing incidence and warming have been observed over several decades (Omumbo et al., 2011). Modelling suggests that the gradual warming is inducing an amplified nonlinear response in malaria incidence (Alonso et al., 2011). A detailed review concluded that decadal temperature changes have played at least a minor role in these malaria trends in the East African highlands (*low confidence*; Chaves and Koenraadt, 2010).

Box 18-5 | Detection, Attribution, and Traditional Ecological Knowledge

Indigenous and local peoples often possess detailed knowledge of climate change that is derived from observations of environmental conditions over many generations. Consequently, there is increasing interest in merging this traditional ecological knowledge (TEK)—also referred to as indigenous knowledge—with the natural and social sciences in order to better understand and detect climate change impacts (Huntington et al., 2004; Parry et al., 2007; Salick and Ross, 2009; Green and Raygorodetsky, 2010; Ford et al., 2011; Diemberger et al., 2012). TEK, however, does not simply augment the sciences, but rather stands on its own as a valued knowledge system that can, together with or independently of the natural sciences, produce useful knowledge for climate change detection or adaptation (Agrawal, 1995; Cruikshank, 2001; Hulme, 2008; Berkes, 2009; Byg and Salick, 2009; Maclean and Cullen, 2009; Wohling, 2009; Ziervogel and Opere, 2010; Ford et al., 2011; Herman-Mercer et al., 2011).

Cases in which TEK and scientific studies both detect the same phenomenon offer a higher level of confidence about climate change impacts and environmental change (Huntington et al., 2004; Laidler, 2006; Krupnik and Ray, 2007; Salick and Ross, 2009; Gamble et al., 2010; Green and Raygorodetsky, 2010; Alexander et al., 2011; Cullen-Unsworth et al., 2012). Evidence is available in particular from Nordic and Mountain peoples, for example, from Peru's Cordillera Blanca mountains (Bury et al., 2010; Carey, 2010; Baraer et al., 2012; Carey et al., 2012b), Tibet (Byg and Salick, 2009), and Canada (Nichols et al., 2004; Laidler, 2006; Krupnik and Ray, 2007; Ford et al., 2009; Aporta et al., 2011). TEK can also inspire scientists to study new issues in the detection of climate change impacts. In one case, experienced Inuit weather forecasters in Baker Lake, Nunavut, Canada, reported that it had become increasingly difficult for them to predict weather, suggesting an increase of weather variability and anomalies in recent years. To test Inuit observations, scientists analyzing hourly temperature data over a 50-year period confirmed that afternoon temperatures fluctuated much more during springtime during the last 20 years—precisely when Inuit forecasters noted unpredictability—than they had during the previous 30 years (Weatherhead et al., 2010).

Despite frequent confluence between TEK and scientific observations, there are sometimes discrepancies between them, indicating uncertainty in the identification of climate change impacts. They can arise because TEK and scientific studies frequently focus on different and distinct scales that make comparison difficult. Local knowledge may fail to detect regional environmental changes while scientific regional or global scale analyses may miss local variation (Wohling, 2009; Gamble et al., 2010). Furthermore, TEK-based observations and related interpretations necessarily need to be viewed within the context of the respective cultural, social, and political backgrounds (Agrawal, 1995). Therefore, a direct translation of TEK into a natural science perspective is often not feasible.

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18.4.5. Human Security

A small number of studies have examined the connection between the collapse of civilizations and large-scale climate disruptions such as severe or prolonged drought. However, both the detection of a climate change effect and an assessment of the importance of its role can be made only with *low confidence* owing to limitations on both historical understanding and data. Some studies have suggested that levels of warfare in Europe and Asia were relatively high during the Little Ice Age (Parker, 2008; Brook, 2010; Tol and Wagner, 2010; White, 2011; Zhang et al., 2011), but for the same reasons the detection of the effect of climate change and an assessment of its importance can be made only with *low confidence*. There is no evidence of a climate change effect on interstate conflict in the post-World War II period.

Most recent research in this area has focused on the relationship between interannual climate variability in temperature, precipitation, and other climate variables and civil conflict, with most studies focusing on Africa (Hsiang et al., 2013; see also Section 12.5). A number of studies have identified statistical relationships (Miguel et al., 2004; Hendrix and Glaser, 2007; Hsiang et al., 2011), but the results have been challenged (Buhaug et al., 2010; Theisen et al., 2011; Buhaug and Theisen, 2012; Slettebak, 2012) on both technical and substantive grounds. The issue is further complicated by the focus on interannual variability—rather than climate change—and civil conflict. Though a plausible argument could be made that climate change has increased interannual variability and has, therefore, contributed positively to the rate of civil conflict, this argument has not been tested in the literature. For these reasons, neither the detection of an effect of climate change on civil conflict nor an assessment of the magnitude of such an effect can currently be made with a degree of confidence.

Several studies have examined links between climate variability and small-scale communal violence (Adano et al., 2012; Butler and Gates, 2012; Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012; Theisen, 2012). As with larger-scale civil conflict, this work has focused on climate

Table 18-4 | Cases of regional livelihood impacts associated with weather- and climate-related events, inter-annual climate variability, or climate change (see also Table 18-3; Section 13.2.1.1).

Impacted population	Climate-related driver	Impact on livelihood	Reference
Small-scale farmers, Ghana	Drought (past 20–30 years)	Landscape transformation causing emotional distress, sense of loss of belonging	Tschakert et al. (2013)
Middle-class farmers, Australia	Drought (2000s)	Landscape transformation, income loss from agriculture, social conflict, poverty	Alston (2011)
Arctic indigenous peoples	Warming (past decades)	Changing ice and snow conditions, dwindling access to hunting grounds	Section 28.2.4; Table 18-9; Hovelsrud et al. (2008); Ford (2009a); Brubaker et al. (2011); Arctic Council (2013); Crate (2013)
Urban populations in Maputo, Accra, Nairobi, Lagos, Kampala	Flood frequency and severity increase (1990s and 2000s)	Direct impacts on people and loss of physical assets (e.g., housing)	Douglas et al. (2008); Adelekan (2010)
Industry workers in India	Temperature variability and heat waves (1960s to present)	Decrease of fully workable days since 1960; limited ability to carry out physical work; health impacts	Ayyappan et al. (2009); Balakrishnan et al. (2010); Dash and Kjellström (2011)
Farmers in Subarnabad, Bangladesh	Sea level rise (~1980s to present)	Salt water intrusion; shift from agriculture to shrimp farming; loss of agricultural livelihoods	Pouliotte et al. (2009)
Women farmers, Ghana	Rainfall-related climate variability (~1990s and 2000s)	Adaptation practices in agriculture produce gender inequalities.	Carr (2008)
Cambodian rice farmers	Warming, rainfall-related climate variability (1980s to present)	Shift in income generation patterns between men and women	Resurreccion (2011)
Poor children in Africa and Latin America	Weather- and climate-related events (1980s to present)	Food price shocks, reduced caloric intake, physical stunting, long-term effects such as reduced lifetime earnings	Alderman (2010)
Smallholder farmers in highlands of Bolivia	Locally perceived changes in temperature means and extremes, and rainfall seasonality (~1990s and 2000s)	Stress on household resources due to need to respond to increasing plant pests; switching to other crop types or livestock	McDowell and Hess (2012)

variability rather than on climate change, so neither the detection of the effect of climate change nor an assessment of its magnitude can currently made with a degree of confidence.

Finally, efforts have been made to establish a link between high temperatures and violent crime (Anderson, 1987; Field, 1992; Anderson, 2001; Rotton and Cohn, 2001; Butke and Sheridan, 2010; Breetzke and Cohn, 2012; Gamble and Hess, 2012). However, the findings remain controversial with other studies identifying non-climate factors as explaining variations in the rate of violent crime (Kawachi et al., 1999; Fajnzylber et al., 2002; Neumayer, 2003; Cole and Gramajo, 2009). Again, the focus in this work has been on weather rather than climate and, in light of this and the equivocal nature of the results, neither the detection of a climate change effect nor an assessment of its magnitude can currently be made with a degree of confidence.

The impact of future climate change on human displacement and migration has been identified as an emerging risk (Section 19.4.2.1). The social, economic, and environmental factors underlying migration are complex and varied (see, e.g., Black et al., 2011) and it has not been possible to detect the effect of observed climate change nor assess its magnitude with any degree of confidence (see also Section 12.4.1.1). Migration in response to climate-related events has been identified in sub-Saharan Africa (Marchiori et al., 2012), with evidence from North America a subject of disagreement (Auffhammer and Vincent, 2012; Feng et al., 2012; Feng and Oppenheimer, 2012).

18.4.6. Livelihoods and Poverty

The vulnerability of the world's poor to climate change, and more generally the sensitivity of many livelihood aspects to climate variability, has been shown in this and earlier IPCC reports (see Chapter 13). However, available research about climate-related effects on livelihood and poverty has focused on impacts of climate extremes or year to year climate variability rather than long-term climatic trends, resulting in a paucity of evidence on observed impacts of climate change on livelihoods and poverty. Moreover, detection of changes in livelihood aspects is often difficult due to a lack of observations (Section 13.2.1), while multiple confounding factors and lack of both adequate climate data and system understanding preclude attribution (Nielsen and Reenberg, 2010).

Table 18-4 summarizes examples of impacts on livelihoods related to climatic trends, climate variability, and extreme weather events. Impacted natural assets include land, water, fish stocks, and livestock (Osbahr et al., 2008; Bunce et al., 2010). There is growing concern about negative effects of climate change and ocean acidification on marine and coastal fisheries, and the livelihoods of fisherfolks (Cooley and Doney, 2009; Badjeck et al., 2010); however, there are no studies evaluating observed impacts.

Climate-related impacts disproportionately affect poor populations, thus increasing social and economic inequalities, both in urban and rural areas, and in low-, middle-, and high-income countries (Sections 13.1.4, 13.2.1). Evidence for poor people in high-income nations being disproportionately affected by extreme weather events comes, for instance, from 2005 U.S. Hurricane Katrina (Elliott and Pais, 2006; Bullard and Wright, 2010; see also Section 13.2.1.5) or severe drought in Australia (Alston, 2011). Glacial lake outburst floods in the Peruvian Andes also affected different populations depending on their degree of exposure, level of vulnerability, race, ethnicity, and socioeconomic class (Carey, 2010; Carey et al., 2012b). Owing to gender-specific roles within the household, communities, and wider sociopolitical and institutional networks, a gender bias has been found in observations of impacts of extreme weather events and climate variability (Carr, 2008; Arora-Jonsson, 2011; Nightingale, 2011; see also Box 13-1).

Poor people living in hazard exposed areas in Africa and Latin America were increasingly affected by floods and landslides in the 1990s and 2000s (*high confidence*; Handmer et al., 2012); however, most of this trend was due to increased urbanization in such areas (Douglas et al., 2008; Hardoy and Pandiella, 2009). There is evidence of a decline in average precipitation in West Africa since 1960 (Lacombe et al., 2012), including repeated droughts (Dietz et al., 2004; Armah et al., 2011), which in some cases has been partly attributed to anthropogenic climate forcing (Held et al., 2005; Jenkins et al., 2005; Biasutti and Giannini, 2006). However, there is only *limited evidence* of changes in poverty among affected small-holder and subsistence farmers that can be attributed to climate drivers such as rainfall decline and droughts (Section 13.2.1).

Livelihoods of indigenous people in the Arctic have been identified as among the most severely affected by climate change, including food security aspects, traditional travel and hunting, and cultural values and references (Hovelsrud et al., 2008; Ford et al., 2009; Ford, 2009a,b; Beaumier and Ford, 2010; Pearce et al., 2010; Olsen et al., 2011; Eira, 2012; Crate, 2013; see also Box 18-5, Table 18-9). Impacts of rising temperatures, increased variability, and weather extremes on crops and livestock of indigenous people in highlands were reported from Tibet Autonomous Region, China (Byg and Salick, 2009), and the Andes of Bolivia (McDowell and Hess, 2012).

18.5. Detection and Attribution of Observed Climate Impacts across Regions

Since the AR4, significant new knowledge about detected impacts of recent climate change has been gained from all continents and oceans

Table 18-5 | Observed impacts of climate change reported since AR4 on mountains, snow, and ice, over the past several decades, across major world regions, with descriptors for (1) the confidence in detection of a climate change impact; (2) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers; (3) the main climatic driver(s) causing the impacts; (4) the reference behavior of the system in the absence of climate change; and (5) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature. Absence of climate change impacts from this table does not imply that such impacts have not occurred.

	Mountains, snow and ice	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
Africa	Retreat of tropical highland glaciers in East Africa	Mölg et al. (2008, 2012); Taylor et al. (2009)	*Very high*	Major	Warming, drying	No change	*High*
Europe	Retreat of Alpine, Scandinavian, and Icelandic glaciers	WGI AR5 Section 4.3.3; Bauder et al. (2007); Björnsson and Pálsson (2008); Paul and Haeberli (2008); WGMS (2008); Zemp et al. (2009); Andreassen et al. (2012); Marzeion et al. (2012); Gardner et al. (2013)	*Very high*	Major	Warming	No change	*High*
	Increase in rock slope failures in western Alps	Sections 18.3.1.3 and 23.3.1.4; Fischer et al. (2012); Huggel et al. (2012a)	*High*	Major	Warming	No change	*Medium*
Asia	Permafrost degradation in Siberia, Central Asia, and the Tibetan Plateau	WGI AR5 Section 4.7.2; Section 24.4.2.2; Romanovsky et al. (2010); Yang et al. (2013)	*High*	Major	Warming	No change	*High*
	Shrinking mountain glaciers across most of Asia	WGI AR5 Section 4.3.3; Section 24.4.1.2; Box 3-1; Bolch et al. (2012); Cogley (2012); Gardelle et al. (2012); Kääb et al. (2012); Yao et al. (2012); Gardner et al. (2013); Stokes et al. (2013)	*High*	Major	Warming	No change	*Medium*
Australasia	Substantial reduction in ice and glacier ice volume in New Zealand	WGI AR5 Section 4.3.3; Table 25-1; Chinn et al. (2012)	*High*	Major	Warming	No change	*Medium*
	Significant decline in late-season snow depth at three out of four alpine sites in Australia 1957–2002	Table 25-1; Nicholls (2006); Hennessy et al. (2008)	*High*	Major	Warming	No change	*Medium*
North America	Shrinkage of glaciers across western and northern North America	WGI AR5 Section 4.3.3; Gardner et al. (2013)	*High*	Major	Warming	No change	*High*
	Decreasing amount of water in spring snowpack in western North America 1960–2002	Stewart et al. (2005); Mote (2006); Barnett et al. (2008)	*High*	Major	Warming	No change	*High*
South and Central America	Shrinkage of Andean glaciers	WGI AR5 Section 4.3.3; Section 27.3.1.1; Table 27-3; Vuille et al. (2008); Bradley et al. (2009); Jomelli et al. (2009); Poveda and Pineda (2009); Marzeion et al. (2012); Gardner et al. (2013); Rabatel et al. (2013)	*High*	Major	Warming	No change	*High*
Polar regions	Decreasing Arctic sea ice cover in summer	WGI AR5 Section 4.2.2.1; ACIA (2005); AMAP (2011)	*Very high*	Major	Air and ocean warming, change in ocean circulation	No change	*High*
	Reduction in ice volume in Arctic glaciers	WGI AR5 Section 4.3.3; ACIA (2005); Nuth et al. (2010); AMAP (2011); Gardner et al. (2011, 2013); Moholdt et al. (2012)	*Very high*	Major	Warming	No change	*High*
	Decreasing snow cover across the Arctic	Section 28.2.3.1; AMAP (2011); Callaghan et al. (2011)	*High*	Major	Warming	No change	*Medium*
	Widespread permafrost degradation, especially in the southern Arctic	Section 28.2.1.1; AMAP (2011); Olsen et al. (2011)	*High*	Major	Warming	No change	*High*
	Ice mass loss along coastal Antarctica	WGI AR5 Sections 4.3.3, 4.4, and 10.5.2.1; Gardner et al. (2013); Miles et al. (2013)	*Medium*	Major	Warming	No change	*Medium*

Table 18-6 | Observed impacts of climate change reported since AR4 on rivers, lakes, and soil moisture, over the past several decades, across major world regions, with descriptors for (1) the confidence in detection of a climate change impact; (2) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers; (3) the main climatic driver(s) causing the impacts; (4) the reference behavior of the system in the absence of climate change; and (5) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature. Absence of climate change impacts from this table does not imply that such impacts have not occurred.

	Rivers, lakes, and soil moisture	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
Africa	Reduced discharge in West African rivers	d'Orgeval and Polcher (2008); Dai et al. (2009); Di Baldassarre et al. (2010)	*Medium*	Major	Reduced precipitation	No change	*Low*
	Lake surface warming and water column stratification increases in the Great Lakes and Lake Kariba	Section 22.3.2.2; Tierney et al. (2010); Ndebele-Murisa et al. (2011); Powers et al. (2011)	*High*	Major	Warming	No change	*High*
	Increased soil moisture drought in the Sahel since 1970, partially wetter conditions since 1990	Section 22.2.2.1; Hoerling et al. (2006); Giannini et al. (2008); Greene et al. (2009); Seneviratne et al. (2012)	*Medium*	Major	Change in precipitation	No change	*Medium*
Europe	Changes in the occurrence of extreme river discharges and floods	Section 23.2.3; Schmocker-Fackel and Naef (2010); Beniston et al. (2011); Cutter et al. (2012); Vorogushyn and Merz (2012); Kundzewicz et al. (2013)	*Low*	Minor	Change in precipitation; change in extreme precipitation	No change	*Very low*
Asia	Changes in water availability in many Chinese rivers	Table SM24-4; Zhang et al. (2007); Zhang, S. et al. (2008)	*High*	Minor	Change in precipitation	Changes due to land use	*Low*
	Increased flow in several rivers in China due to shrinking glaciers	Casassa et al. (2009); Li et al. (2010); Zhang, Y. et al. (2008)	*High*	Major	Warming	No change	*High*
	Earlier timing of maximum spring flood in Russian rivers	Section 28.2.1.1; Shiklomanov et al. (2007); Tan et al. (2011)	*High*	Major	Warming	No change	*Medium*
	Reduced soil moisture in North Central and Northeast China 1950–2006	Sections 24.3.1 and 24.4.1.2; Sheffield and Wood (2007); Wang, A. et al. (2011); Seneviratne et al. (2012)	*Medium*	Major	Warming; change in precipitation	No change	*Medium*
	Surface water degradation in parts of Asia	Section 24.4.1.2; Prathumratana et al. (2008); Delpla et al. (2009); Huang et al. (2009)	*Medium*	Minor	Warming; change in precipitation	Changes due to land use	*Medium*
Australasia	Intensification of hydrological drought due to regional warming in Southeast Australia	Table 25-1; Nicholls (2006); Cai et al. (2009)	*Low*	Minor	Warming	No change	*Low*
	Reduced inflow in river systems in southwestern Australia (since the mid-1970s)	Table 25-1; Section 25.5.1; Cai and Cowan (2006); Nicholls (2010)	*High*	Major	Change in precipitation; warming	No change	*High*
North America	Shift to earlier peak flow in snow dominated rivers in western North America	Barnett et al. (2008)	*High*	Major	Warming; change in snow	No change	*High*
	Runoff increases in the midwestern and northeastern USA	Georgakakos et al. (2013)	*High*	Minor	Change in precipitation; warming	No change	*Medium*
South and Central America	Changes in extreme flows in Amazon River	Section 27.3.1.1; Butt et al. (2011); Wang, G. et al. (2011); Espinoza et al. (2013)	*High*	Major	Change in precipitation; change in extreme precipitation	No change	*Medium*
	Changing discharge patterns in rivers in the Western Andes; for major river basins in Colombia discharge has decreased during the last 30–40 years	Section 27.3.1.1; Table 27-3; Vuille et al. (2008); Casassa et al. (2009); Poveda and Pineda (2009); Baraer et al. (2012); Rabatel et al. (2013)	*Medium*	Major	Warming	No change	*Medium*
	Increased streamflow in sub-basins of the La Plata River	Section 27.3.1.1; Pasquini and Depetris (2007); Krepper et al. (2008); Saurral et al. (2008); Conway and Mahé (2009); Krepper and Zucarelli (2010); Doyle and Barros (2011)	*High*	Major	Change in precipitation	Increase due to land use	*High*
Polar regions	Increased river discharge for large circumpolar rivers (1997–2007)	Section 28.2.1.1; Overeem and Syvitsky, (2010)	*High*	Major	Warming; change in precipitation; change in snow cover	No change	*Low*
	Winter minimum river flow increase in most sectors of the Arctic	Section 28.2.1.1; Tan et al. (2011)	*High*	Major	Warming; change in snow cover	No change	*Medium*
	Increasing lake water temperatures 1985–2009, prolonged ice-free seasons	Section 28.2.1.1; Callaghan et al. (2010); Schneider and Hook (2010)	*Medium*	Major	Warming	No change	*Medium*
	Thermokarst lakes disappear due to permafrost degradation in the low Arctic, new ones created in areas of formerly frozen peat	Section 28.2.1.1; Riordan et al. (2006); Marsh et al. (2008); Prowse and Brown (2010)	*High*	Major	Warming	No change	*High*
Small islands	Increased water scarcity in Jamaica	Gamble et al. (2010); Jury and Winter (2010)	*Low*	Minor	Change in precipitation	Increase due to water use	*Very low*

Table 18-7 | Observed impacts of climate change reported since AR4 on terrestrial ecosystems, over the past several decades, across major world regions, with descriptors for: (1) the confidence in detection of a climate change impact; (2) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers; (3) the main climatic driver(s) causing the impacts; (4) the reference behavior of the system in the absence of climate change; and (5) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature. Absence of climate change impacts from this table does not imply that such impacts have not occurred.

	Terrestrial ecosystems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
Africa	Tree density decreases in Western Sahel and semi-arid Morocco	Section 22.3.2.1; Gonzalez et al. (2012); Le Polain de Waroux and Lambin (2012)	*Medium*	Major	Change in precipitation	Changes due to land use	*Medium*
	Range shifts of several southern plants and animals: South African bird species polewards; Madagascan reptiles and amphibians upwards; Namib aloe contracting ranges	Table 22-3; Foden et al. (2007); Raxworthy et al. (2008); Hockey and Midgley (2009); Hockey et al. (2011)	*High*	Major	Warming	Changes due to land use	*Medium*
	Wildfires increase on Mt. Kilimanjaro	Table 22-3; Hemp (2005)	*Medium*	Major	Warming; drying	No change	*Low*
Europe	Earlier greening, earlier leaf emergence and fruiting in temperate and boreal trees	Section 4.3.2.1; Menzel et al. (2006)	*High*	Major	Warming	No change	*High*
	Increased colonization of alien plant species in Europe	Section 4.2.4.6; Table 23-6; Walther et al. (2009)	*Medium*	Major	Warming	Some invasion	*Medium*
	Earlier arrival of migratory birds in Europe since 1970	Section 4.2.4.6; Table 23-6; Møller et al. (2008)	*Medium*	Major	Warming	No change	*Medium*
	Upward shift in tree line in Europe	Section 18.3.2.3; Table 23-6; Gehrig-Fasel et al. (2007); Lenoir et al. (2008)	*Medium*	Major	Warming	Changes due to land use	*Low*
	Increasing burnt forest areas during recent decades in Portugal and Greece	Table 23-6; Camia and Amatulli (2009); Hoinka et al. (2009); Costa et al. (2011); Koutsias et al. (2012)	*High*	Major	Warming; change in precipitation	Some increase due to land use	*High*
Asia	Changes in plant phenology and growth in many parts of Asia (earlier greening), particularly in the north and the east	Sections 4.3.2.1 and 24.4.2.2; Figure 4-4; Ma and Zhou (2012); Panday and Ghimire (2012); Shrestha et al. (2012); Ogawa-Onishi and Berry (2013)	*High*	Major	Warming	No change	*Medium*
	Distribution shifts in many plant and animal species, particularly in the north of Asia, upwards in elevation or polewards	Sections 4.3.2.5 and 24.4.2.2; Figure 4-4; Moiseev et al. (2010); Chen et al. (2011); Jump et al. (2012); Ogawa-Onishi and Berry (2013)	*High*	Major	Warming	No change	*Medium*
	Invasion of Siberian larch forests by pine and spruce during recent decades	Section 24.4.2.2; Kharuk et al. (2010); Lloyd et al. (2011)	*Medium*	Major	Warming	No change	*Low*
	Advance of shrubs into the Siberian tundra	Sections 4.3.3.4, 24.4.2.2, and 28.2.3.1; Henry and Elmendorf (2010); Blok et al. (2011)	*High*	Major	Warming	No change	*High*
Australasia	Changes in genetics, growth, distribution, and phenology of many species, in particular birds, butterflies and plants in Australia	Table 25-3; Chambers (2008); Chessman (2009); Green (2010); Kearney et al. (2010); Keatley and Hudson (2012); Chambers et al. (2013b)	*High*	Major	Warming	Fluctuations due to variable local climates, land use, pollution, invasive species	*High*
	Expansion of some wetlands and contraction of adjacent woodlands in southeast Australia	Table 25-3; Keith et al. (2010)	*Medium*	Major	Change in precipitation; warming	No change	*Low*
	Expansion of monsoon rainforest at expense of savannah and grasslands in north Australia	Table 25-3; Banfai and Bowman (2007); Bowman et al. (2010)	*Medium*	Major	Change in precipitation; increased CO_2	No change	*Medium*
	Migration of glass eels advanced by several weeks in Waikato River, New Zealand	Table 25-3; Jellyman et al. (2009)	*Medium*	Major	Warming	No change	*Low*

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of the world, as assessed in Chapters 22 to 30 of this report. Tables 18-5 to 18-9 summarize impacts in major natural and human systems, at the local to continental scale, for which assessment of the role of climate as one driver has been possible. The following paragraphs provide a summary of recent climate changes in these regions along with notes about particular challenges in the regional assessments.

For much of *Africa*, knowledge about recent climate change is limited, owing to weak climate monitoring and gaps in coverage that continue to exist. On the other hand, the low natural temperature variability over the continent allows earlier detection of warming signals. Thus there is *medium* to *high confidence* in regional warming, with *low* to *high confidence* in attribution to anthropogenic emissions. A main regional feature has been the drying of the Sahel during the decades following 1970, but that trend has halted during the most recent decade (Hoerling et al., 2006; Giannini et al., 2008; Greene et al., 2009; Seneviratne et al., 2012). African natural and human systems present challenges for the potential detection and attribution of responses to climate change. Given the weak spatial and temporal variations in temperature, there is smaller scope for migrational and phenological

Table 18-7 (continued)

	Terrestrial ecosystems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
North America	Phenology changes and species distribution shifts upward in elevation and northward across multiple taxa	Section 26.4.1; Parmesan and Galbraith (2004); Parmesan (2006); Kelly and Goulden (2008); Moritz et al. (2008); Tingley et al. (2009)	*High*	Major	Warming	No change	*Medium*
	Increased wildfire frequency in subarctic conifer forests and tundra	Section 28.2.3.1; Mack et al. (2011); Mann et al. (2012)	*High*	Major	Warming	No change	*Medium*
	Regional increases in tree mortality and insect infestations in forests	Section 26.4.2.1; Van Mantgem et al. (2009); Peng et al. (2011)	*Medium*	Minor	Warming	No change	*Low*
	Increase in wildfire activity, fire frequency and duration, and burnt area in forests of the western US and boreal forests in Canada	Box 26-2; Gillett et al. (2004); Westerling et al. (2006); Girardin et al. (2013)	*High*	Minor	Warming; change in precipitation	Changes due to land use and fire management	*Medium*
South and Central America	Increased tree mortality and forest fire in the Amazon	Section 4.3.3.1.3; Phillips et al. (2009)	*Medium*	Minor	Warming	No change	*Low*
	Degrading and receding rainforest in the Amazon	Sections 18.3.2.4, 27.2.2.1, and 27.3.2.1; Etter et al. (2006); Nepstad et al. (2006); Oliveira et al. (2007); Wassenaar et al. (2007); Killeen et al. (2008); Nepstad and Stickler (2008)	*Low*	Minor	Warming	Deforestation and land degradation	*Low*
Polar regions	Increase in shrub cover in tundra in North America and Eurasia	Section 28.2.3.1.2; Tape et al. (2006); Walker et al. (2006); Henry and Elmendorf (2010); Blok et al. (2011); Elmendorf et al. (2012); Tape et al. (2012)	*High*	Major	Warming	No change	*High*
	Advance of Arctic tree-line in latitude and altitude	Section 28.2.3.1.2; AMAP (2011); Hedenås et al. (2011); Van Bogaert et al. (2011)	*High*	Major	Warming	No change	*Medium*
	Loss of snow-bed ecosystems and tussock tundra	Section 28.2.3.1.2; Björk and Molau (2007); Molau (2010a); Hedenås et al. (2011); Callaghan et al. (2013)	*High*	Major	Warming; change in precipitation	No change	*High*
	Impacts on tundra animals from increased ice layers in snow pack, following rain-on-snow events	Section 28.2.3.1.3; Callaghan et al. (2011); Hansen et al. (2013)	*Medium*	Major	Change in precipitation; warming	No change	*Medium*
	Changes in breeding area and population size of subarctic birds, due to snowbed reduction and/or tundra shrub encroachment	Molau (2010b); Callaghan et al. (2013)	*High*	Major	Warming	No change	*Medium*
	Increase in plant species ranges in the West Antarctic Peninsula and nearby islands over the past 50 years	Section 28.2.3.2; Fowbert and Smith (1994); Parnikoza et al. (2009)	*High*	Major	Warming	No change	*High*
	Increasing phytoplankton productivity in Signy Island lake waters	Quayle et al. (2002); Laybourn-Parry (2003)	*High*	Major	Warming	No change	*High*
Small islands	Changes in tropical bird populations in Mauritius	Section 29.3.2; Senapathi et al. (2011)	*Medium*	Major	Change in precipitation	No change	*Medium*
	Decline of an endemic plant in Hawai'i	Krushelnycky et al. (2013)	*Medium*	Major	Warming; change in precipitation	No change	*Medium*
	Upward trend in tree lines and associated fauna on high-elevation islands	Section 29.3.2; Benning et al. (2002); Jump et al. (2006)	*Low*	Minor	Warming	No change	*Low*

responses to anthropogenic climate change than in other parts of the world. High-quality monitoring is relatively sparse in time and space, and is often unsuitable for detecting changes across margins and borders where responses to climate change are most expected. The dearth of studies examining attribution questions means it is currently difficult to estimate the degree to which studies are selectively published based on results, and thus to determine whether each attribution study is indicative only of local reasons for concern or if it is more generally representative of a broader domain.

Amongst all continents, *Europe* has the longest tradition in climate monitoring. Warming has been occurring across the continent in all seasons, with an associated decreasing frequency of cold extremes and increasing frequency of hot extremes (Seneviratne et al., 2012). The Mediterranean basin has been getting drier, while northern areas have been getting wetter (Section 23.2.2.1), with a general increase in the frequency of extreme wet events everywhere (Seneviratne et al., 2012).

Asia spans a particularly wide range of climate types. Warming has been observed throughout the continent, with northern areas among the fastest warming on the planet. Precipitation trends vary geographically, with a weaker Indian monsoon (WGI AR5 Section 14.2.2.1) and contrasting increasing and drying trends over coastal and inland China (Section 24.3).

Warming has occurred in *Australasia* during the past century, with hot extremes becoming more frequent and cold extremes becoming less

Table 18-8 | Observed impacts of climate change reported since AR4 on coastal and marine ecosystems, over the past several decades, across major world regions, with descriptors for (1) the confidence in detection of a climate change impact; (2) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers; (3) the main climatic driver(s) causing the impacts; (4) the reference behavior of the system in the absence of climate change; and (5) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature. Absence of climate change impacts from this table does not imply that such impacts have not occurred.

	Coastal and marine ecosystems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
Africa	Decline in coral reefs in tropical African waters	Sections 30.5.3.1.2 and 30.5.4.1.5; Baker et al. (2008); Carpenter et al. (2008); Ateweberhan et al. (2011)	*High*	Major	Ocean warming	Decline due to human impacts	*High*
Europe	Northward shifts in the distributions of zooplankton, fish, seabirds, and benthic invertebrates in the northeast Atlantic	Box 6-1; Table 6-2; Sections 6.3.1, 23.6.5, and 30.5.1.1; Beaugrand et al. (2009); Philippart et al. (2011)	*High*	Major	Ocean warming	No change	*High*
	Northward and depth shift in distribution of many fish species across European seas	Sections 6.3.1, 23.6.4, 23.6.5, and 30.5.3.1; Table 6-2; Perry et al. (2005); Pörtner et al. (2008); Beaugrand et al. (2009, 2010); Beaugrand and Kirby (2010); Hermant et al. (2010); Philippart et al. (2011)	*High*	Major	Ocean warming	No change	*Medium*
	Phenology changes in plankton in the northeast Atlantic	Box 6-1; Sections 6.3.1, 23.6.5, and 30.5.1.1; Beaugrand et al. (2002, 2009); Edwards and Richardson (2004); Philippart et al. (2011)	*Medium*	Major	Ocean warming	No change	*Medium*
	Spread of warm water species into the Mediterranean	Sections 23.6.5 and 30.5.3.1.5; Boero et al. (2008); Lasram and Mouillot (2009); Raitsos et al. (2010)	*High*	Major	Ocean warming	Changes due to invasive species and human impacts	*Medium*
Asia	Decline in coral reefs in tropical Asian waters	Sections 24.4.3.2 and 30.5.1.4.3; McLeod et al. (2010); Krishnan et al. (2011); Coles and Riegl (2012)	*High*	Major	Ocean warming	Decline due to human impacts	*High*
	Northward range extension of coral in the East China Sea and western Pacific, and a predatory fish in the Sea of Japan	Section 24.4.3.2; Yamano et al. (2011); Tian et al. (2012); Ogawa-Onishi and Berry (2013)	*Medium*	Major	Ocean warming	No change	*Medium*
	Shift from sardines to anchovies in the western North Pacific	Sections 6.3.1 and 6.3.6; Table 6-2; Takasuka et al. (2007, 2008)	*Medium*	Major	Ocean warming	Fluctuations due to fisheries	*Low*
	Increased coastal erosion in Arctic Asia	Section 24.4.3.2; Razumov (2010); Forbes (2011); Lantuit et al. (2011)	*Medium*	Major	Permafrost degradation, ocean warming, change in sea ice	No change	*Low*
Australasia	Southward shifts in the distribution of marine species near Australia	Table 25-3; Ling et al. (2009b); Pitt et al. (2010); Neuheimer et al. (2011); Wernberg et al. (2011b)	*High*	Major	Ocean warming	Changes due to short-term environmental fluctuations; fishing and pollution	*Medium*
	Change in timing of migration of seabirds in Australia	Section 25.6.2.1; Chambers et al. (2011, 2013a)	*Medium*	Major	Air and ocean warming	No change	*Low*
	Increase in coral bleaching in the Great Barrier Reef and Western Australian Reefs	Sections 6.3.1.4, 6.3.1.5, and 25.6.2.1; Table 25-3; Cooper et al. (2008); De'ath et al. (2009, 2012); Moore et al. (2012)	*High*	Major	Ocean warming	Pollution; physical disturbance	*High*
	Changes in coral disease patterns at Great Barrier Reef	Section 25.6.2.1; Table 25-3; Bruno et al. (2007); Sato et al. (2009); Dalton et al. (2010)	*Medium*	Major	Ocean warming	Pollution	*Medium*
North America	Northward shifts in the distributions of northwest Atlantic fish species	Section 30.5.1.1; Nye et al. (2009, 2011); Lucey and Nye (2010)	*High*	Major	Ocean warming	No change	*High*
	Changes in mussel beds along the west coast of the USA	Smith et al. (2006); Menge et al. (2008); Harley (2011)	*High*	Major	Ocean warming	No change	*High*
	Changes in migration and survival of salmon in the northeast Pacific	Table 6-2; Eliason et al. (2011); Kovach et al. (2012)	*High*	Major	Ocean warming	No change	*High*
	Increased coastal erosion in Alaska and Canada	Sections 18.3.1.1 and 18.3.3.1; Mars and Houseknecht (2007); Forbes (2011); Lantuit et al. (2011)	*High*	Major	Permafrost degradation; ocean warming, change in sea ice	No change	*Medium*

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Table 18-8 (continued)

	Coastal and marine ecosystems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
South and Central America	Increase in coral bleaching in the western Caribbean	Section 27.3.3.1; Guzman et al. (2008); Manzello et al. (2008); Carilli et al. (2009); Eakin et al. (2010)	*High*	Major	Ocean warming	Pollution; physical disturbance	*High*
	Mangrove degradation on north coast of South America	Section 27.3.3.1; Alongi (2008); Lampis (2010); Polidoro et al. (2010); Giri et al. (2011)	*Low*	Minor	Ocean warming	Degradation due to pollution and land use	*Low*
Polar regions	Increased coastal erosion across the Arctic	Sections 18.3.1.1, 18.3.3.1, 28.2.4.2, and 28.3.4; Mars and Houseknecht (2007); Razumov (2010); Forbes (2011); Lantuit et al. (2011)	*Medium*	Major	Permafrost degradation; ocean warming, change in sea ice	No change	*Medium*
	Negative effects on non-migratory Arctic species	Section 28.2.2.1; Laidre et al. (2008); Amstrup et al. (2010); McIntyre et al. (2011)	*High*	Major	Atmospheric and ocean warming; circulation change; change in sea ice	No change	*High*
	Decreased reproductive success in Arctic seabirds	Section 28.2.2.1.2; Gaston et al. (2009); Grémillet and Boulinier (2009)	*Medium*	Major	Air and ocean warming; change in ocean circulation; change in sea ice	No change	*Medium*
	Decline in Southern Ocean seals and seabirds	Section 28.2.2.2; Croxall et al. (2002); Patterson et al. (2003); Jenouvrier et al. (2005); Véran et al. (2007); Forcada et al. (2008); Trathan et al. (2011); Chambers et al. (2013a)	*High*	Major	Ocean warming	No change	*Medium*
	Reduced thickness of foraminiferal shells in the Southern Ocean	Sections 6.3.2 and 28.2.2.2; Moy et al. (2009)	*Medium*	Major	Ocean acidification	No change	*Medium*
	Reduced density of krill in the Scotia Sea	Atkinson et al. (2004); Trivelpiece et al. (2011)	*Medium*	Major	Ocean warming; change in ocean circulation; change in sea ice	No change	*Medium*
Small islands	Increased coral bleaching near many tropical small islands	Section 29.3.1.2; Alling et al. (2007); Bruno and Selig (2007); Oxenford et al. (2008); Sandin et al. (2008)	*High*	Major	Ocean warming	Degradation due to fishing and pollution	*High*
	Degradation of mangroves, wetlands, and seagrass around small islands	Section 29.3.1.2; McKee et al. (2007); Gilman et al. (2008); Schleupner (2008); Krauss et al. (2010); Marbà and Duarte (2010); Rankey (2011)	*Low*	Minor	Sea level rise; atmospheric and ocean warming	Degradation due to other disturbances	*Very low*
	Increasing flooding and erosion	Section 29.3.1.1; Webb (2006); Webb (2007); Yamano et al. (2007); Cambers (2009); Novelo-Casanova and Suarez (2010); Storey and Hunter (2010); Ballu et al. (2011); Rankey (2011); Ford (2012); Romine et al. (2013)	*Low*	Minor	Sea level rise	Erosion due to human activities, natural erosion, and accretion	*Low*
	Degradation of groundwater and freshwater ecosystems due to saline intrusion	Section 29.3.2; White et al. (2007a,b); Ross et al. (2009); Carreira et al. (2010); Terry and Falkland (2010); White and Falkland (2010); Goodman et al. (2012)	*Low*	Minor	Sea level rise	Degradation due to pollution and groundwater pumping	*Low*

frequent (Section 25.2, Table 25-1). Winters in southern areas of Australia have become drier in the past few decades and the northwest has become wetter, and precipitation increased over the south and west of both islands of New Zealand. Though there have been no significant trends in drought frequency over Australia, regional warming may have increased their hydrological intensity, and fire weather increased since 1973 in Australia (Table 25-1; Clarke et al., 2012).

North America spans a wide range of climate types and observed climate changes. While the northwest has been among the fastest warming regions on the planet, the southeast of the USA has experienced slight cooling (Section 26.2.2.1). Hot extremes have been becoming more frequent while cold extremes and frost days have been becoming less frequent over the past several decades. Trends in precipitation over western parts of the continent are strongly influenced by the variability of the ENSO, with a matching drying and decreasing snowpack. The intensity of precipitation events has been increasing over most of the continent, but trends in dryness are spatially heterogeneous (Section 26.2.2.1). Intense tropical storms have increased in the North Atlantic over the past several decades (WGI AR5 Section 2.6.3).

Most of *Central and South America* has warmed over the past half century, except for a slight cooling over a western coastal strip (Section 27.2.1). Precipitation over much of Central and South America is strongly influenced by the ENSO, with accompanying long-term variability. There has been a reduction in the number of dry summer months in the southern half of the continent, while trends over the Amazon are sensitive to the selection of time period (Section 27.2.1). More frequent and severe droughts in the Amazon have been linked to warming (Marengo et al., 2011a).

The areas of largest observed warming are all *polar*: the northwest of North America, northern Asia, and the Antarctic Peninsula. The nature of polar regions means that warming can lead to large changes in other

Table 18-9 | Observed impacts of climate change reported since AR4 on human and managed systems, over the past several decades, across major world regions, with descriptors for (1) the confidence in detection of a climate change impact; (2) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers; (3) the main climatic driver(s) causing the impacts; (4) the reference behavior of the system in the absence of climate change; and (5) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature. Absence of climate change impacts from this table does not imply that such impacts have not occurred.

	Human and managed systems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
Africa	Adaptative responses to changing rainfall by South African farmers	Section 13.2.1.2; Thomas et al. (2007)	*Low*	Major	Change in precipitation	Changes due to economic conditions	*Very low*
	Decline in fruit-bearing trees in Sahel	Wezel and Lykke (2006); Maranz (2009)	*Medium*	Major	Change in precipitation	No change	*Low*
	Malaria increases in Kenyan highlands	Section 11.5.1.1; O'Meara et al. (2010); Alonso et al. (2011); Stern et al. (2011)	*Low*	Minor	Warming	Changes due to vaccination, drug resistance, demography, and livelihoods	*Low*
	Reduced fisheries productivity of Great Lakes and Lake Kariba	Sections 7.2.1.2, 13.2.1.1, and 22.3.2.2; Descy and Sarmento (2008); Hecky et al. (2010); Ndebele-Murisa et al. (2011); Marshall (2012)	*Low*	Minor	Warming	Changes due to fisheries management and land use	*Low*
Europe	Shift from cold-related mortality to heat-related mortality in England and Wales	Sections 18.4.4 and 23.5.1; Christidis et al. (2010)	*Medium*	Major	Warming	Changes due to exposure and health care	*Low*
	Impacts on livelihoods of Sámi people in northern Europe	Eira (2012); Mathiesen et al. (2013)	*Medium*	Major	Warming	Economic and sociopolitical changes	*Medium*
	Stagnation of wheat yields in some countries in recent decades	Section 23.4.1; Brisson et al. (2010); Kristensen et al. (2011)	*High*	Minor	Warming	Increase due to improved technology	*Medium*
	Positive yield impacts for some crops, mainly in northern Europe	Figure 7-2; Section 23.4.1; Jaggard et al. (2007); Supit et al. (2010); Gregory and Marshall (2012)	*High*	Minor	Warming	Increase due to improved technology	*Medium*
	Spread of bluetongue virus in sheep, and of ticks across parts of Europe	Section 23.4.2; Arzt et al. (2010); Randolph and Rogers (2010); Van Dijk et al. (2010); Guis et al. (2012); Petney et al. (2012)	*High*	Minor	Warming	No change	*Medium*
Asia	Impacts on livelihoods of indigenous groups in Arctic Russia	Sections 13.2.1.2, 18.4.6, and 28.2.4.2; Table 18-4; Crate (2013)	*Medium*	Major	Warming; change in snow cover; change in sea ice	Economic and sociopolitical changes	*Low*
	Negative impacts on aggregate wheat yields in South Asia	Section 7.2.1; Figure 7-2; Pathak et al. (2003)	*Medium*	Minor	Warming; change in precipitation	Increase due to improved technology	*Medium*
	Negative impacts on aggregate wheat and maize yields in China	Section 7.2.1; Figure 7-2; Tao et al. (2006, 2008, 2012); You et al. (2009); Chen et al. (2010)	*Low*	Minor	Warming	Increase due to improved technology	*Low*
	Increases in a water-borne disease in Israel	Paz et al. (2007)	*Low*	Minor	Warming	No change	*Low*
Australasia	Advance timing of wine-grape maturation in recent decades	Table 25-3; Webb et al. (2012)	*High*	Major	Warming	Advance due to improved management	*Medium*
	Shift in winter versus summer human mortality in Australia	Sections 11.4.1, 18.4.4, and 25.8.1.1; Bennett et al. (2013)	*Medium*	Major	Warming	Changes due to exposure and health care	*Low*
	Relocation or diversification of agricultural activities in Australia	Section 25.7.2; Box 25-5; Gaydon et al. (2010); Howden et al. (2010); Park et al. (2012); Thorburn et al. (2012)	*Medium*	Minor	Warming	Changes due to policy, markets, and short-term climate variability	*Low*
Central and South America	More vulnerable livelihood trajectories for indigenous Aymara farmers in Bolivia, due to water shortage	Section 13.1.4; McDowell and Hess (2012)	*Medium*	Major	Warming	Increasing social and economic stress	*Medium*
	Increase in agricultural yields and expansion of agricultural areas in southeastern South America	Section 27.3.4.1; Magrin et al. (2007); Barros (2010); Hoyos et al. (2013)	*Medium*	Major	Precipitation increase	Increase due to improved technology	*Medium*

Continued next page →

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Table 18-9 (continued)

	Human and managed systems	References	Confidence in detection	Role of climate	Climate driver	Reference behavior	Confidence in attribution
North America	Impacts on livelihoods of indigenous groups in the Canadian Arctic	Sections 18.4.6 and 28.2.4.2; Table 18-4; Hovelsrud et al. (2008); Ford et al. (2009); Beaumier and Ford (2010); Pearce et al. (2010); Brubaker et al. (2011)	*Medium*	Major	Warming; change in snow cover; change in sea ice	Economic and sociopolitical changes	*Medium*
Polar regions	Impact on livelihoods of Arctic indigenous peoples	Sections 18.4.6 and 28.2.4.2; Table 18-4; Hovelsrud et al. (2008); Ford et al. (2009); Beaumier and Ford (2010); Pearce et al. (2010); Eira (2012); Crate (2013); Mathiesen et al. (2013)	*Medium*	Major	Warming; change in snow cover; change in sea ice	Economic and sociopolitical changes	*Medium*
	Increase of shipping traffic across the Bering Strait	Section 28.2.6.1.3; Figure 28-4; Robards (2013)	*Medium*	Major	Warming; change in sea ice	No change	*Medium*
Small islands	Increased degradation of coastal fisheries due to direct effects and effects of increased coral reef bleaching	Box CC-CR; Sections 18.3.3.3, 18.4.1.2, 29.3.1.2, and 30.6.2.1	*Low*	Minor	Ocean warming	Coastal fisheries degraded by overfishing and pollution	*Low*

aspects of the climate system, in particular the observed decrease in summer sea ice cover, earlier thaw, earlier spring runoff, and thawing of permafrost (Section 28.2).

Despite the widely accepted high vulnerability of many *small islands* to climate change, there are only few formal studies on observed impacts. Detection of climate change impacts in small islands is challenging due to the strong presence of other anthropogenic drivers of local environmental change. Attribution is further challenged by the strong influence of natural variability compared to incremental changes of climate drivers and by the lack of long-term monitoring and high-quality data.

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18.6. Synthesis: Emerging Patterns of Observed Impacts of Climate Change

18.6.1. Approach

The AR4 precursor of the current chapter (Rosenzweig et al., 2007) provided a geographically distributed empirical analysis of correlations across numerous detailed and localized studies of changing systems (elaborated more later in Rosenzweig et al., 2008). Rather than expand that approach, this synthesis organizes the findings on detection and attribution of observed impacts of climate change aiming at covering the full disciplinary, sectoral, and geographic diversity of impacts, drawn directly from sectoral and regional assessments in this report.

A key motivation for the effort in assessing these observed changes is the possibility that observed impacts could constitute indications of future expected changes. Observed losses in glacial volume, for example, lend important additional plausibility to model-based expectations that sustained warming could result in additional ice loss. Such extrapolation faces important limitations, however. First, owing to the complex nonlinear behavior of most natural and human systems, it cannot always be assumed that past impacts scale linearly to future impacts. Likewise, absence of past impacts cannot constitute evidence against the possibility of future impacts. Nonetheless, detection and attribution of observed impacts may serve as part of the foundation for a climatic risk analysis. To do so, the total body of observed impacts needs to undergo a synthetic assessment pointing toward any conceivable risks.

Virtually all observed impacts of climate change are of regional nature (Section 18.5); however, the occurrence of similar impacts in many regions of the world emerges more strongly with every IPCC assessment. The global pattern emerging from the sum of observed regional impacts is therefore analyzed in Section 18.6.2. The current body of observations provides improved evidence of major impacts in natural and human systems that have "cascading" consequences for other systems—key examples for these are synthesized in Section 18.6.3. Finally, Section 18.6.4 aims to establish current conditions concerning the risk analysis model formulated earlier by the IPCC through the establishment of a limited number of "Reasons for Concern" (RFC)—the risk analysis itself is part of Chapter 19 of this report.

18.6.2. The Global Pattern of Regional Impacts

The global pattern of observed climate change differs strongly for the different climate variables. Broadly, more warming has occurred at higher latitudes than in the Tropics, while the pattern of rainfall changes is highly complex (WGI AR5 Chapter 2). Taken together, this provides a heterogeneous pattern of climate change across the globe. In addition, some natural and human systems (and the regions in which they occur) are more vulnerable to changing climate than others. Crucially, observational records are of highly heterogeneous nature: not only do low-income countries report fewer impacts than high-income countries, but there is also a significant shortage of observations from remote areas such as the deep sea or sparsely populated mountains and deserts. Taken together, it is therefore natural to expect an uneven distribution of detected impacts (Figure 18-3).

The outstanding finding about the global pattern of observed impacts is that, on all continents and across major ocean regions, significant impacts have now been observed. Many of these concern systems which are affected directly by warming (the cryosphere, marine systems), but a growing number of observed impacts have been shown to be the result of a combination of changing temperature and precipitation (agricultural and hydrological systems).

The global distribution of observed impacts shown in Figure 18-3 demonstrates that analyses can now detect impacts in systems strongly

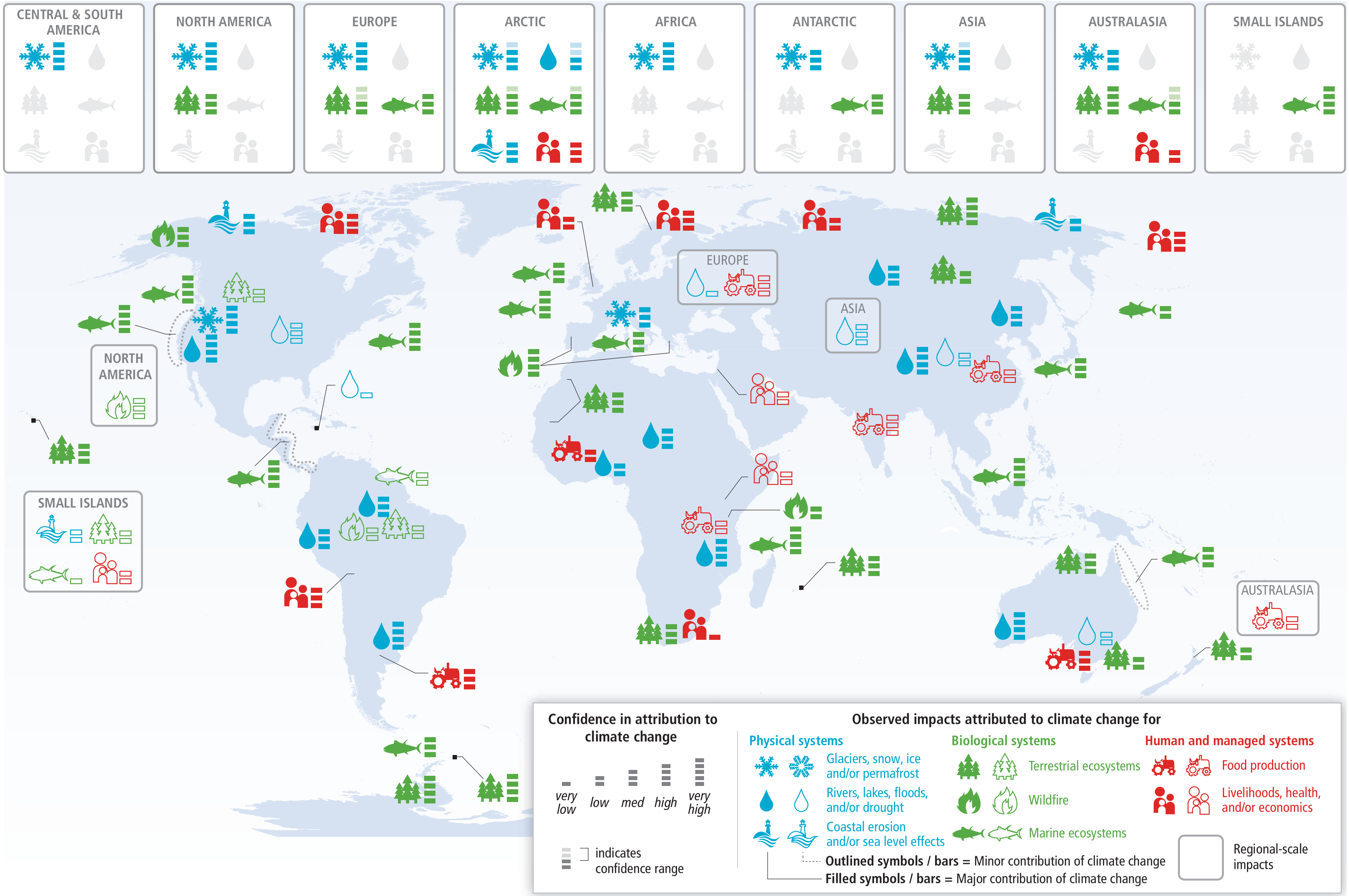

Figure 18-3 | Global patterns of observed climate change impacts reported since AR4. Each filled symbol in the top panels indicates a class of systems for which climate change has played a major role in observed changes in at least one system within that class across the respective region, with the range of confidence in attribution for those region-wide impacts indicated by the bars. Regional-scale impacts where climate change has played a minor role are shown by outlined symbols in a box in the respective region. Sub-regional impacts are indicated with symbols on the map, placed in the approximate area of their occurrence. The impacted area can vary from specific locations to broad areas such as a major river basin. Impacts on physical (blue), biological (green), and human (red) systems are differentiated by color. This map represents a graphical synthesis of Tables 18-5, 18-6, 18-7, 18-8, and 18-9. Absence of climate change impacts from this figure does not imply that such impacts have not occurred.

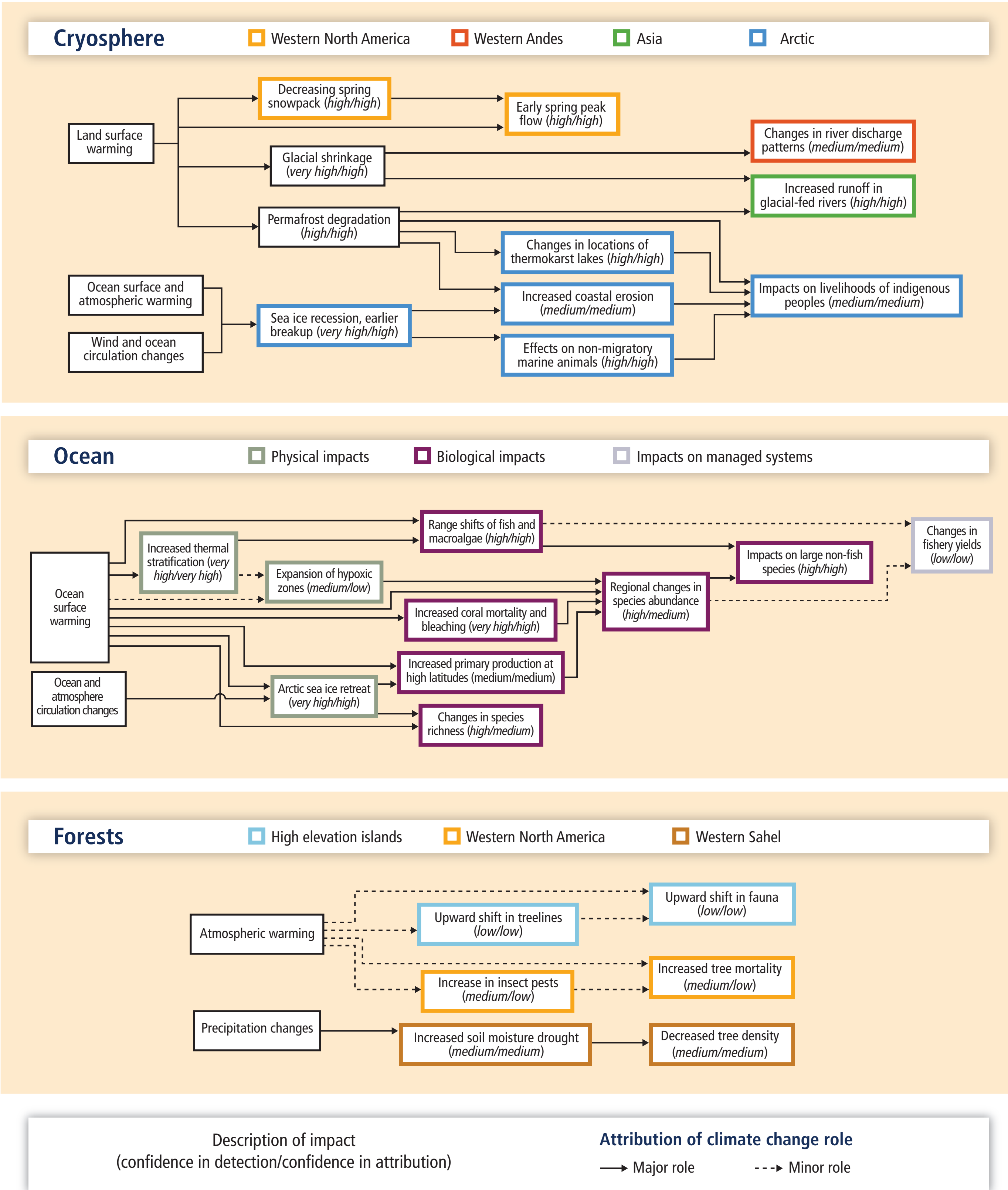

Figure 18-4 | Major systems where new evidence indicates interconnected, "cascading" impacts from recent climate change through several natural and human subsystems. Text in parentheses indicates confidence in the detection of a climate change effect and the attribution of observed impacts to climate change. The role of climate change can be major (solid arrow) or minor (dashed arrow). Confidence is assessed in Sections 18.3, 18.4, 18.5, and 18.6.

influenced by confounding factors and hence where climate change plays only a minor role. The most outstanding examples for this are agricultural systems where impacts now emerge in a number of places. An identified minor role of climate for some impact does not imply that this role is less important. New studies now identify more clearly such roles even when they are masked by stronger confounding factors such as environmental degradation or improved technology. Examples for such studies include assessments of mangrove degradation, caused by both warming and pollution (Giri et al., 2011), or changes in Inuit livelihoods, influenced by both warming and social changes (Ford et al., 2009). Enhanced research efforts would probably add additional observations of impacts with a minor, but important, role of climate to the global map.

18.6.3. Cascading Impacts

Many impacts of climate change are direct cause-effect relationships, such as reduction of glacier volume following higher temperatures. Others may be mediated through impacts on intermediary systems (e.g., Johnson et al., 2011). Enhanced evidence of observed impacts of climate change, and improved research methodologies now allow attribution of effects at various stages along the causal impact chain (Figure 18-4). Within the cryosphere, changes in atmospheric and ocean properties of the climate have driven changes in the cryosphere on the land surface, the land subsurface, and the ocean surface. These changes have in turn led to changes in multiple aspects of hydrology and ecosystems, and in some regions (e.g., the Arctic) changes in these systems have impacted human livelihoods (Xu et al., 2009). Within most ocean regions, warming has led to a number of observed impacts on biota, some of which are mediated through the effect of warming on the ocean's thermal stratification or on sea ice. Impacts tend to propagate up the food chain, eventually affecting large mammals, birds, reptiles, and humans. In forests and woodlands, climate change impacts on trees have been transmitted through pests, fire, and drought, while impacts on forests have also been observed to affect the forest fauna. In all these cases, confidence in detection and attribution to observed climate change decreases for effects further down each impact chain.

18.6.4. Reasons for Concern

To synthesize its findings in support of a risk analysis the IPCC in its Third Assessment Report (TAR) developed the "Reasons for Concern" (RFC) concept (Smith et al., 2001), which was adopted for a second time in IPCC AR4 (IPCC, 2007b), and elaborated in Smith et al. (2009). It is further developed in Chapter 1 of this report and employed extensively in Chapter 19 for the risk framing approach of WGII AR5. In this chapter, the goal is to establish, qualitatively, the evidence of impacts already observed that are relevant to these categories (names of categories have been adapted for consistency across Chapters 1, 18, and 19; see below). The broad definitions of the RFC continue to imply significant overlap; hence some observed impacts are referred to under more than one RFC.

The RFC *Risks to Unique and Threatened Systems* is concerned with the potential for increased damage to, or irreversible loss of, systems such as physical systems, ecosystems, and human livelihoods, all of which are known to be highly sensitive to temporal and/or spatial variations in climate. Figure 18-5 displays confidence levels in the current evidence

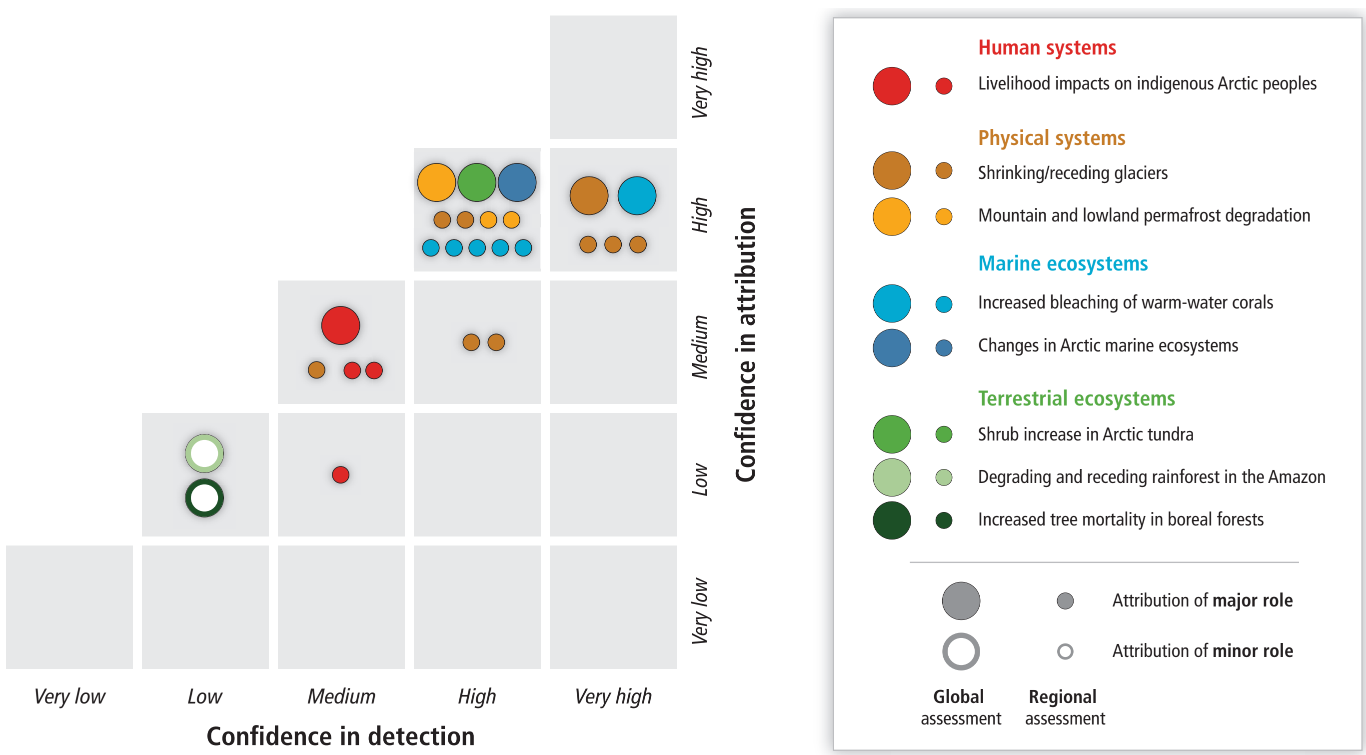

Figure 18-5 | Confidence in detection and attribution of observed impacts on "Unique and Threatened Systems" as a result of recent climate change. Global assessments (large circles) and regional assessments (small circles) are discussed in Sections 18.3.1.1 and 18.3.2.4, Box 18-2, and Tables 18-2 and 18-5 through 18-9. Attribution assessments are for a minor (outlined circles) or major (filled circles) role of climate change, as indicated.

derived from detection and attribution studies of such observed impacts. Changes in the three indicated main natural systems (physical systems, marine and terrestrial ecosystems) have at least *high confidence* in attribution of a major role of climate change, with regional assessments also tending to have similar confidence. There is at least *medium confidence* in attribution of a major role for at least one each of ecosystems, physical systems, and human systems.

The unique and threatened systems with strongest detection and attribution evidence cover the Arctic, warm-water coral reefs, and mountains. In the Arctic, climate change has played a major role in observed impacts on glaciers, permafrost, the tundra, marine ecosystems, and livelihoods of indigenous peoples (at least *medium confidence*), reflecting large-scale changes across both natural and human systems and across the physical and ecological sub-regions. Evidence for the detection and attribution of shrinkage and recession of glaciers comes from all continents, while evidence for attribution of coral bleaching spans a similarly broad area of the tropical oceans (see Figure 18-5).

The RFC *Risks Associated with Extreme Weather Events* "tracks increases in extreme events with substantial consequences for societies and natural systems" (Smith et al., 2009, p. 4134). Besides episodic (e.g., coral bleaching) and chronic (e.g., erosion) impacts of extreme weather events, this RFC also considers increased frequency of extreme impact events (e.g., floods), even if their climate drivers are not wholly episodic in nature. A change in the risk of impacts of extreme weather events could be caused by a change in the probability, intensity, or sequencing of the weather event itself (which are manifestations of recent climate change), or by a change in exposure, vulnerability, or the resilience of the impacted system. Trends have been noted for extreme weather hazards. Temperature extremes have changed in most regions over the past half century, with more frequent hot events and less frequent cold events (*high confidence*; Hansen et al., 2012; Seneviratne et al., 2012; Coumou et al., 2013; see WGI AR5 Section 2.6.1). Some regions have also experienced increasingly frequent periods of heavy precipitation events (*medium confidence*; Min et al., 2011), while other regions have experienced positive or negative trends in measures of dry spells (Seneviratne et al., 2012). Current evidence does not, however, indicate sustained global trends in tropical cyclone or extratropical cyclone activity (Seneviratne et al., 2012; see WGI AR5 Section 2.6.3).

Table 18-10 summarizes new evidence concerning this RFC. Generally, the strongest evidence of detected impacts related to extremes concerns warm-water corals where bleaching has been linked directly to high-temperature spells (Box 18-2; Baker et al., 2008; Strong et al., 2011). Outside of these coral reef systems, however, evidence for extreme event impacts is limited and mostly local. Overall, a number of trends in observed impacts on natural systems have been documented that indicate changing risks driven by changes in extreme weather (*medium confidence*), but any similar trends in human systems have not been detected against large shifts in exposure, vulnerability, and resilience.

Table 18-10 | Confidence in detection and attribution of observed trends in impacts related to extreme weather. The assessment, for the impacts on various systems, is of attribution of those trends to climate change and of the confidence in existence of observed trends in that extreme weather. The assessment of confidence in detection is against the specified reference behavior, while the assessment of attribution is for the indicated minor or major role of observed climate trends. The confidence statements refer to a globally balanced assessment.

Impacts and impact events					Climate/weather drivers		Reference
Observed trend	Confidence in detection	Reference behavior	Confidence in attribution	Role of climate change	Observed trend	Confidence in existence of trend	
Earlier timing and decreasing magnitude of snowmelt floods	*Medium*	No change	*Medium*	Major	Decreasing snow pack	*High*	Section 3.2.7; Tables 18-5 and 18-6; WGI AR5 Section 4.5; Seneviratne et al. (2012)
					Increasing heavy precipitation amounts	*Medium*	
Changes in flood frequency and magnitude in non-snowmelt–fed rivers	*Low*	Changes due to land use	*Low*	Minor	Trends in extreme rainfall amounts	*Medium*	Min et al. (2011); WGI AR5 Sections 2.5.2 and 2.6.2
					Increased evapotranspiration and decreased soil moisture	*Medium*	
Increased coastal erosion in low and mid latitudes	*Very low*	Erosion due to shoreline modification and natural processes	*Very low*	Minor	Increasingly frequent high storm waves and surges	*High*	Sections 5.4.2 and 18.3.3.1; WGI AR5 Section 3.7.5
Increased erosion of Arctic coasts	*Medium*	No change	*Medium*	Major	Lack of sea ice protection from wind storms	*Very high*	Table 18-8; Sections 18.3.1.1, 24.4.3.2, 28.2.4.2, and 28.3.4; Forbes (2011); WGI AR5 Section 4.2.2
Increase in high-mountain rock slope failures	*Low*	No change	*Low*	Major	Increasingly frequent and intense heat waves	*Medium*	Figure 18-2; Huggel et al. (2012a); Seneviratne et al. (2012); Allen and Huggel (2013); WGI AR5 Section 2.6.1
Increased coral bleaching	*Very high*	Changes due to pollution, physical disturbance, and fishing	*High*	Major	Increasingly frequent extreme hot surface waters	*Very high*	Tables 18-2 and 18-8; Sections 5.2.4.2, 6.3.1, 24.4.3.2, 27.3.3.1, 29.3.1.2, 30.3.1.1, and 30.5; Box 18-2
Increased monetary losses	*Low*	Changes due to exposure and wealth	*Low*	Minor	Increased frequency of storms	*Low*	Sections 10.7.3 and 18.4.3.1; Seneviratne et al. (2012); WGI AR5 Section 2.6
					Increased frequency of floods	*Low*	
Increased heat related mortality	*Low*	Changes due to exposure and health care	*Very low*	Minor	Increased frequency of heat waves	*Medium*	Section 11.4.1; Seneviratne et al. (2012);WGI AR5 Section 2.6.1

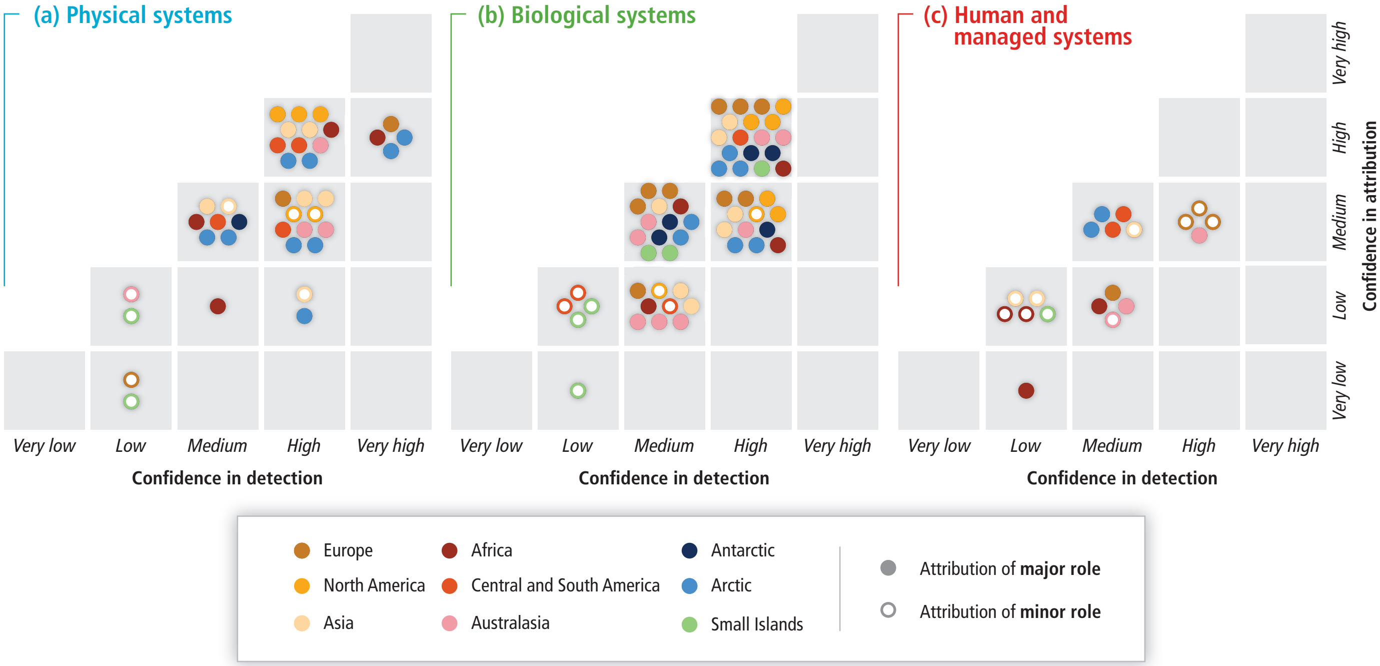

Figure 18-6 | Confidence in detection of observed climate change impacts in physical natural systems, biological systems, and human and managed systems across regions, and confidence in attribution of such trends to observed climate change as a major or minor driver (based on assessments developed in Tables 18-5 to 18-9). (a) Physical systems include the cryosphere, hydrology, and coastal processes; (b) biological systems refer to changes in marine and terrestrial ecosystems, including wildfires; and (c) human and managed systems summarize impacts on food production, health, human livelihoods, and economics.

The RFC *Risks Associated with the Distribution of Impacts* focuses on the disparities of impacts between regions, countries, and populations. The survey of recent studies presented in Section 18.5 indicates that, while evidence for detected impacts is still more exhaustive from Europe and North America, considerable confidence in conclusions has been developed elsewhere since the AR4, particularly in Central and South America and Australasia (Figure 18-3). It is no longer the case that higher confidence levels of detected impacts are restricted to any particular region (Figure 18-6).

The qualitative conclusion that observed impacts on human and managed systems have now been detected with at least *medium confidence* on all inhabited continents is new and noteworthy. However, the number of systems with detectable impacts is only an indicative metric of coverage, because many options exist for aggregation and disaggregation of evidence. Thus this synthesis of detection and attribution studies does not, at this time, provide evidence of differing severity of impacts between continents. Throughout its assessments, the IPCC has repeatedly noted the significant disparity between the vulnerability of countries, regions, and social groups, related to differences in adaptive capacity (e.g., Wilbanks et al., 2007). Nevertheless, additional coverage of detection and attribution studies is required for broad evaluation of social disparities in impacts.

The original intent of the category now labeled as *Risks Associated with Aggregate Impacts* was to assess those economic impacts, damages, and risks that are specifically driven by climate change at a globally aggregated level, using unified monetary metrics. Recognizing the limits of calibrated monetarization of impacts, the scope of this RFC has been expanded over time to also include non-monetary metrics (Smith et al., 2009). Table 18-11 lists various aggregate systems of near-global extent for which the following two conditions apply: there is some form of calibrated metric for comparison of impacts across space and subsystems, and the evidence for detection and attribution of the impacts has sufficient geographical coverage to count as spatially representative sample.

Confidence in such large-scale detection is, again, highest in cryospheric systems (expressed in glacier volume or permafrost active layer thickness), but climate change has also affected ecosystems (expressed as net productivity or carbon stocks, ranging from *medium* to *high confidence*) and some human systems (crop yields, losses due to extreme events, ranging from *low* to *medium confidence*) according to the listed aggregate measures. Thus, several globally aggregated impacts of recent climate change have now been identified.

The RFC *Risks Associated with Large-Scale Singular Events* "represents the likelihood that certain phenomena (sometimes called singularities or tipping points) would occur, any of which may be accompanied by very large impacts" (Smith et al., 2009). Several studies have identified "tipping elements" in the Earth system that exhibit nonlinear behavior with potentially strong feedbacks on the Earth system (Lenton et al., 2008; Leadley et al., 2010). For observed impacts, the concern translates into a question of the possible presence of "early warning signals" for discontinuities that may be derived from monitoring changes in some climate or natural systems (Collie et al., 2004; deYoung et al., 2008; Andersen et al., 2009; Lenton, 2011).

For the Arctic region, new evidence indicates a biophysical regime shift is taking place, with cascading impacts on physical systems, ecosystems, and human livelihoods. For Arctic marine biota, the rapid reduction of summer ice cover causes a tipping element that is now severely

Table 18-11 | Confidence in detection of impacts on aggregate impact measures against the specified reference behavior and confidence in attribution of the specified role of climate change in those observed changes.

Global aggregated impact	Confidence in detection	Reference behavior	Confidence in attribution	Role of climate change	Reference
Glacier ice volume reduction	*Very high*	No change	*High*	Major	Sections 3.2.2 and 18.3.1.1
Permafrost degradation and increase of active layer thickness	*High*	No change	*High*	Major	Section 18.3.1.1
Increase in terrestrial net primary production and carbon stocks	*High*	Changes due to nitrogen deposition, afforestation, and land management	*Low*	Major	Section 18.3.2.2
Negative yield impacts on global wheat and maize yields	*Medium*	Changes due to technology, practice, and coverage	*Medium*	Minor	Section 18.4.1.1; Figure 7-2
Increase in monetary losses due to extreme weather	*Low*	Changes due to exposure and wealth	*Low*	Minor	Sections 10.7.3 and 18.4.3.1

affecting pelagic ecosystems as well as ice-dependent mammals such as seals and polar bears (*high confidence*; Duarte et al., 2012a; see also Tables 18-2, 18-8; Section 28.2.2.1). On land, thawing of Arctic permafrost and shrub encroachment on the tundra have been driven by warming and prolongation of the growing season (*high confidence*; Sections 4.3.3.4, 18.3.2.4, 24.4.2.2; Tables 18-5, 18-7; Figure 4-4). Permafrost degradation has contributed to widespread hydrological changes including lake formation or disappearance within a few years' time (*high confidence*; Prowse and Brown, 2010; Callaghan et al., 2013; Table 18-6), while increasing winter rains have had consequences for the tundra food webs (*medium confidence*; Post et al., 2009; Callaghan et al., 2013; Hansen et al., 2013). Indigenous people throughout the Arctic are impacted by these changes (Eira, 2012; Crate, 2013; see also Section 18.4.6). In summary, several indicators of the ongoing regime shift in the entire Arctic land-sea socio-ecological system can be interpreted as a warning sign for a large-scale singular event (Post et al., 2009; CAFF, 2010; Callaghan et al., 2010; AMAP, 2011; Duarte et al., 2012b; Figure 18-3; Tables 18-5, 18-7 to 18-9; Section 28.2).

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Reef building corals are in rapid decline in many regions, and climate change is one of the major drivers (*high confidence*; Box 18-2). This irreversible loss of biodiversity has significant feedbacks within the marine biosphere, and significant consequences for regional marine ecosystems as well as the human livelihoods that depend on them (Hoegh-Guldberg and Bruno, 2010; Richardson et al., 2012). The growing evidence for presently ongoing change and its attribution to warming gained since the AR4 strengthens the conclusion that increased mass bleaching of corals constitutes a strong warning signal for the singular event that would constitute the irreversible loss of an entire biome.

Dieback and degradation in the boreal forests as well as the Amazonian rainforest have also been identified as potential tipping elements in the Earth system, due to their large extent and the possible feedbacks with the carbon cycle (Lenton et al., 2008; Leadley et al., 2010; Marengo et al., 2011b; see also Section 4.3.3.1). For the boreal forest, increases in tree mortality have been observed in many regions, including widespread dieback related to insect infestations and fire in North America (Sections 4.3.3.1, 26.4.2.1). Taken together, these may be seen as indicators of an ongoing regime shift in the boreal forest, but there is only *low confidence* in attribution to climate change (Section 18.3.2.4; Figure 4-4). In the humid tropical forests of the Amazon basin, increased tree turnover (both mortality and growth) and enhanced drought risks have been observed during recent decades. However, the main reason for concern is the interaction between climate change, deforestation, and the high susceptibility of forests to fire, which together could produce positive feedbacks leading to degradation of forests in large areas of the Amazon (Malhi et al., 2009). Currently, there is only *low confidence* in attribution of observed ecosystem changes in the Amazon to climate change. In conclusion, there is insufficient evidence from observed climate change impacts to support a climate-related warning sign of possible large-scale singular events in the boreal and Amazonian forest.

18.6.5. Conclusion

Detection and attribution studies evaluate the agreement between observations of change in a system and process understanding of its causes, whether these are due to climate change or other forces. This sets a higher bar for establishing confidence in the assessment of past changes than is generally applied to the projections of future changes, because observational evidence has important gaps, while plausibility of future changes is established on the basis of process knowledge only. Despite this constraint, the body of evidence on observed impacts of recent climate change demonstrates increasing coverage of the Earth and its various subsystems, including human livelihoods. Increasingly, there is also evidence for complex changes in interconnected systems.

This analysis lends new qualitative support to four out of the five RFCs established by earlier IPCC assessments. Specifically, evidence is notable for risks to unique and threatened systems, risks stemming from extreme weather events, risks associated with globally aggregated impacts, and—in terms of early warnings—risks associated with large-scale discontinuities. Only the spatial or social disparities covered under "Risks Associated with the Distribution of Impacts" are still insufficiently studied to permit a synthesis of available observations for the characterization of a global concern. While the Arctic stands out as a region with *robust evidence* of impacts across numerous systems, current detection and attribution literature does not address whether the severity of those impacts differs from other regions. The Arctic region, warm-water coral reef systems, and mountain glaciers feature strongly in the observational evidence discussed for all the RFCs, but there are also important observations from impacted hydrological systems and human systems, including agriculture.

The evidence gathered since the AR4 on detection and attribution of observed impacts from climate change has reached a level at which it can inform evaluation of many of the aspects of present-day climate change risk as described by the RFCs. In particular, the geographical distribution of studies is reaching the point where assessment of the global nature of impacts is possible:

- There is now *robust evidence* of observed changes in natural systems in all of the regional groupings used in this report. Climate change has played a major role in observed changes in various components of the cryosphere on all continents (*high confidence*). Climate change has also driven observed changes in terrestrial ecosystems on six continents (*high confidence*, the exception being *low confidence* in Central and South America) and on some small islands (*medium confidence*), and for marine ecosystems surrounding six continents and some small islands (*high confidence*, with evidence lacking for Africa).
- There is *new and stronger evidence* of the detection of impacts in human systems on the inhabited continents. There is at least *medium confidence* in detection of impacts on food production in all the inhabited continents except North America.
- While the current detection and attribution literature does not reveal observational evidence of geographical differences in the severity of climate change impacts between continents, it does indicate that the unique systems of the Arctic region and warm water coral reefs are undergoing rapid changes in response to observed warming in ways that are potentially irreversible.

18.7. Gaps, Research Needs, and Emerging Issues

There are three broad areas relating to the detection and attribution of the impacts of climate change on natural and human systems that require more research. The first concerns the formulation of the relevant issues and further development of rigorous scientific methods for addressing them. At present, the terms detection and attribution are used in numerous different ways, and, while there is no need for a single definition, more clarity about usage is important. Methods in this area are closely linked to specific formulations of these terms and there is a parallel need to develop, refine, and evaluate them in light of this. For example, statistical methods are commonly used to detect the impact of variations in climate on human and natural systems while controlling for the effect of other factors. Such detection can be valuable in helping to predict the response of systems to projections of future climate change but a positive correlation does not necessarily imply that the system has already changed in response to historical climate change. A second example is the growing use of methods that combine information from multiple systems— for example, different locations or species— to draw a conclusion about systems in general. More conceptual work is needed to develop the basis for such ecological meta-analysis and the interpretation of its results.

A second area in which more work is needed is data collection and monitoring. Globally, environmental data are still insufficient for monitoring the impacts of climate change. In addition, developed countries are typically over-represented in impact studies because of their comparable wealth in socioeconomic data. Because the level of economic development is extremely important in determining the impacts of climate change, this over-representation probably gives rise to a distorted picture of the global impacts of climate change.

Finally, this chapter stresses the need to base detection and attribution studies on a scientific understanding of the system in question and the way in which climate change (and other factors) might affect it rather than on relatively simple correlational analysis. This is particularly important for human systems and at least some natural systems in which the combined effect of climate change and other factors is complex and historical adaptation to climate change must be expected. Further development, refinement, and evaluation of both conceptual and process-based models of the human-environment system will be essential for improved conclusions about detection and attribution.

Frequently Asked Questions

FAQ 18.1 | Why are detection and attribution of climate impacts important?

To respond to climate change, it is necessary to predict what its impacts on natural and human systems will be. As some of these predicted impacts are expected to already have occurred, detection and attribution provides a way of validating and refining predictions about the future. For example, one of the clearest predicted ecological impacts of climate is a poleward shift in the ranges of plant and animal species. The detection in historical data of a climate-related shift in species ranges would lend credence to this prediction, and the assessment of its magnitude would provide information about the likely magnitude of future shifts.

Frequently Asked Questions

FAQ 18.2 | Why is it important to assess impacts of all climate change aspects, and not only impacts of anthropogenic climate change?

Natural and human systems are affected by both natural and anthropogenic climate change, operating locally, regionally, and/or globally. To understand the sensitivity of natural and human systems to expected future climate change, and to anticipate the outcome of adaptation policies, it is less important whether the observed changes have been caused by anthropogenic climate change or by natural climate fluctuations. In the context of this chapter, all known impacts of climate change are assessed.

Frequently Asked Questions

FAQ 18.3 | What are the main challenges in detecting climate change impacts?

The detection of climate change impacts addresses the question of whether a system has changed beyond its expected behavior in the absence of climate change. This requires an understanding of both the external and internal factors that affect the system. External factors that can affect natural systems include exploitation, land use changes, and pollution. Even in the absence of changes in external factors, many natural systems exhibit substantial internal variability—such as booms and busts in wild populations—that can last for long periods. For example, to detect the impact of climate change on wild fish stocks, it is necessary to understand the effects of fishing, habitat alteration, and possibly pollution, as well as the internal stock dynamics. In the same way, human systems are affected by social and economic factors that are unrelated to climate change. For example, to detect the impact of climate change on human health, it is necessary to understand the effects of changes in public health measures such as improved sanitation.

Frequently Asked Questions

FAQ 18.4 | What are the main challenges in attributing changes in a system to climate change?

Whereas the detection of climate change impacts addresses the question only of whether or not a system has changed as a result of climate change, attribution addresses the magnitude of the contribution of climate change to such changes. Even when it is possible to detect the impact of climate change on a system, more detailed understanding may be needed to assess the magnitude of this impact in relation to the influences of other external factors and natural variability.

Frequently Asked Questions

FAQ 18.5 | Is it possible to attribute a single event, like a disease outbreak or the extinction of a species, to climate change?

It is possible to detect trends in the frequency or characteristics of a class of weather events like heat waves. Similarly, trends in a certain kind of impact of that class of events can also be detected and attributed, although the influence of other drivers of change, such as policy decisions and increasing wealth, can make this challenging. However, any single impact event also results from the antecedent conditions of the impacted system. Thus though damage from a single extreme weather event may occur against the background of trends in many influencing factors, including climate change, there is always a contribution from random chance.

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19 Emergent Risks and Key Vulnerabilities

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Executive Summary

This chapter assesses climate-related risks in the context of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC). {Box 19.1} Such risks arise from the interaction of the evolving exposure and vulnerability of human, socioeconomic, and biological systems with changing physical characteristics of the climate system. {19.2} Alternative development paths influence risk by changing the likelihood of climatic events and trends (through their effects on greenhouse gases (GHGs) and other emissions) and by altering vulnerability and exposure. {19.2.4, Figure 19-1, Box 19-2}

Interactions of climate change impacts on one sector with changes in exposure and vulnerability, as well as adaptation and mitigation actions affecting the same or a different sector are generally not included or well integrated into projections of risk. However, their consideration leads to the identification of a variety of emergent risks {Box 19-2} that were not previously assessed or recognized (*high confidence*). {19.3} This chapter identifies several such complex system interactions that increase vulnerability and risk synergistically. For example:

- **The risk of climate change to human systems (e.g., agriculture and water supply) is increased by the loss of ecosystem services that are supported by biodiversity** (e.g., water purification, protection from extreme weather events, preservation of soils, recycling of nutrients, and pollination of crops) (*high confidence*). Studies since the Fourth Assessment Report (AR4) broadly confirm that a large proportion of species are at increased risk of extinction at all but the lowest levels of warming. {19.3.2.1, 19.5.1, 19.6.3.5}
- **Risks result from the management of water, land, and energy in the context of climate change.** For example, in some water stressed regions, as groundwater stores that have historically acted as buffers against impacts of climate variations and change are depleted, adverse consequences arise for human systems and ecosystems simultaneously undergoing alteration of regional groundwater resources due to climate change. The production of bioenergy crops to mitigate climate change leads to land conversion (e.g., from food crops and unmanaged ecosystems to energy crops; *high confidence*) and in some scenarios, reduced food security as well as additional GHG emissions over the course of decades or centuries. {19.3.2.2}
- **Climate change has the potential to adversely affect human health by increasing exposure and vulnerability to a variety of stresses.** For example, the interaction of climate change with food security can exacerbate malnutrition, increasing vulnerability of individuals to a range of diseases (*high confidence*). {19.3.2.3}
- **The risk of severe harm and loss due to climate change-related hazards and various vulnerabilities is particularly high in large urban and rural areas in low-lying coastal zones (*high confidence*).** These areas, many characterized by increasing populations, are exposed to multiple hazards and potential failures of critical infrastructure, generating new systemic risks. Cities in Asian megadeltas, where populations are subject to sea level rise, storm surge, coastal erosion, saline intrusion, and flooding, provide an example. {19.2.3, 19.3.2.4, 19.4.2.1, 19.6.1.3.1, 19.6.2.1, 19.7.5, Table 19-4}
- **Spatial convergence of impacts in different sectors creates compound risk in many areas (*medium confidence*).** Examples include the Arctic (where thawing and sea ice loss disrupt land transportation, buildings, other infrastructure, and are projected to disrupt indigenous culture); and the environs of Micronesia, Mariana Island, and Papua New Guinea (where coral reefs are highly threatened due to exposure to concomitant sea surface temperature rise and ocean acidification). {19.3.2.4}

Emergent risks also arise from indirect, trans-boundary, and long-distance impacts of climate change. Adaptive responses and mitigation measures sometimes increase such risks (*high confidence*). {19.4} Human or ecological responses to local impacts of climate change can generate harm at distant places.

- Increasing prices of food commodities on the global market due to local climate impacts, in conjunction with other stressors, decrease food security and exacerbate food insecurity at distant locations. {19.4.1}
- Climate change will bear significant consequences for human migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states (*high confidence*). {19.4.2.1}
- The effect of climate change on conflict and insecurity is an emergent risk because factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change. In numerous statistical studies, the influence of climate variability on violent conflict is large in magnitude (*medium confidence*). {19.4.2.2}
- Many species shift their ranges in response to climate change, adversely affecting ecosystem function and services while presenting new challenges to conservation efforts (*medium confidence*). {19.4.2.3}

- Mitigation measures taken in one location can have long-distance or indirect impacts on biodiversity and/or human systems. For example, the development of biofuels as energy sources can increase food prices (*high confidence*) and affect distant land use practices. {19.4.1, 19.4.3}

Additional risks related to particular biophysical impacts of climate change have arisen recently in the literature in sufficient detail to permit assessment (*high confidence*). {19.5}

- **Risks associated with global temperature rise in excess of 4°C relative to preindustrial levels[1] arise** from severe and widespread impacts on unique and threatened systems, substantial species extinction, extensive loss of ecosystem functioning, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year (*high confidence*) and the potential for traversing thresholds that lead to disproportionately large Earth systems responses (*medium confidence*). {19.5.1}
- **Ocean acidification poses risks to marine ecosystems and the societies that depend on them.** For example, ocean acidification is *very likely* to lead to changes in coral calcification rates. Reduced coral calcification is projected to have impacts of medium to high magnitude on some ecosystem services, including tourism and the provisioning of fishing. {19.5.2}
- **There is increasing evidence in the literature that high ambient carbon dioxide (CO_2) concentrations in the atmosphere will affect human health by increasing the production and allergenicity of pollen and allergenic compounds and by decreasing nutritional quality of important food crops. {19.5.3}**
- **In addition to providing potential climate change abatement benefits, geoengineering poses widespread risks to society and ecosystems.** For example, in some model experiments the implementation of Solar Radiation Management (SRM) for the purpose of limiting global warming leads to ozone depletion and reduces precipitation. In addition, the failure or abrupt halting of SRM risks rapid climate change. {19.5.4}

Global, regional, and local socioeconomic, environmental, and governance trends indicate that vulnerability and exposure of communities or social-ecological systems to climatic hazards related to extreme events are dynamic and thus vary across temporal and spatial scales (*high confidence*). Effective risk reduction and adaptation strategies consider these dynamics and the inter-linkages between socioeconomic development pathways and the vulnerability and exposure of people. Changes in poverty or socioeconomic status, ethnic composition, age structure, and governance had a significant influence on the outcome of past crises associated with climatic hazards. {19.6.1}

Challenges for vulnerability reduction and adaptation actions are particularly high in regions that have shown severe difficulties in governance. Studies confirm that countries that are classified as failed states and afflicted by violence are often not able to reduce vulnerability effectively. Unless governance improves in countries with severe governance failure, risk will increase as a result of climate changes interacting with increased human vulnerability (*high confidence*). {19.6.1.3.3}

***Key risks* inform evaluation of "dangerous anthropogenic interference with the climate system," in the terminology of UNFCCC Article 2. These are potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of hazards linked to climate change and the vulnerability of exposed societies and systems. Key risks were identified in this assessment based on expert judgments made by authors of the various chapters of this report in light of criteria described here {19.2.2.2} and consolidated into the following representative list (*high confidence*).** {19.2.2.2, 19.6.2.1, Table 19-4, Boxes 19-2 and CC-KR} (Roman numerals indicate corresponding entries in Table 19-4; notation at end of each entry indicates corresponding Reasons for Concern (RFCs), discussed below.)

[1] Levels of global mean temperature change are variously presented in the literature with respect to "preindustrial" temperatures in a specified year or period, e.g., 1850–1900. Alternatively, the average temperature within a recent period, e.g., 1986–2005, is used as a baseline. In this chapter, we use both, depending on the literature being assessed. The increase above preindustrial (1850–1900) levels for the period 1986–2005 is estimated at 0.61°C (WGI AR5 Section 11.3.6.3). For example, using these baselines, a 2°C increase above preindustrial levels corresponds to a 1.39°C increase above 1986–2005 levels. We use other baselines on occasion depending on the literature cited and explicitly indicate where this is the case. Climate impact studies often report outcomes as a function of regional temperature change, which can differ significantly from changes in global mean temperature. In most land areas, regional warming is larger than global warming (WGI AR5 Section 10.3.1.1.2). However, given the many conventions in the literature for baseline periods, readers are advised to check carefully and to adjust baseline levels for consistency when comparing outcomes.

i) Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise. [RFC 1-5]
ii) Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions. [RFC 2 and 3]
iii) Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services. [RFC 2-4]
iv) Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas. [RFC 2 and 3]
v) Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings. [RFC 2-4]
vi) Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions. [RFC 2 and 3]
vii) Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic. [RFC 1, 2, and 4]
viii) Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods. [RFC 1, 3, and 4]

Climate change risks vary substantially across plausible alternative development pathways and the relative importance of development and climate change varies by sector, region, and time period; both are important to understanding possible outcomes (*high confidence*). In some cases, there is substantial potential for adaptation to reduce risks, with development pathways playing a key role in determining challenges to adaptation, including through their effects on ecosystems and ecosystem services. {19.6.2.2}

Assessment of the RFC framework pertinent to Article 2 of the UNFCCC has led to evaluations of risk being updated in light of the advances since the AR4. {19.6.3} (All temperature changes are relative to 1986–2005, i.e., "recent." Numbers are indicative of RFC designation in key risk enumeration, above.)

1. **Unique and threatened systems**: Some unique and threatened systems, including ecosystems and cultures, are already at risk from climate change (*high confidence*). The number of such systems at risk of severe consequences is higher with additional warming of around 1°C. Many species and systems with limited adaptive capacity are subject to very high risks with additional warming of 2°C, particularly Arctic-sea-ice and coral-reef systems. {19.6.3.2}
2. **Extreme weather events**: Climate-change-related risks from extreme events, such as heat waves, extreme precipitation, and coastal flooding, are already moderate (*high confidence*) and high with 1°C additional warming (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures (*high confidence*). {19.6.3.3}
3. **Distribution of impacts**: Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Risks are already moderate because of regionally differentiated climate-change impacts on crop production in particular (*medium* to *high confidence*). Based on projected decreases in regional crop yields and water availability, risks of unevenly distributed impacts are high for additional warming above 2°C (*medium confidence*). {19.6.3.4}
4. **Global aggregate impacts**: Risks of global aggregate impacts are moderate for additional warming between 1-2°C, reflecting impacts to both Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss with associated loss of ecosystem goods and services results in high risks around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. {19.3.2.1, 19.5.1, 19.6.3.5}
5. **Large-scale singular events**: With increasing warming, some physical systems or ecosystems may be at risk of abrupt and irreversible changes. Risks associated with such tipping points become moderate between 0-1°C additional warming, due to early warning signs that both warm-water coral reef and Arctic ecosystems are already experiencing irreversible regime shifts (*medium confidence*). Risks increase disproportionately as temperature increases between 1-2°C additional warming and become high above 3°C, due to the potential for a large and irreversible sea level rise from ice sheet loss. For sustained warming greater than some threshold, near-complete loss of the Greenland ice sheet would occur over a millennium or more, contributing up to 7 m of global mean sea level rise. {19.6.3.6}

Impacts of climate change avoided under a range of scenarios for mitigation of GHG emissions are potentially large and increasing over the 21st century (*high confidence*). {19.7.1} Among the impacts assessed here, benefits from mitigation are most immediate for surface ocean acidification and least immediate for impacts related to sea level rise. Because mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades.

Only mitigation scenarios in the most stringent category (i.e., with 2100 CO_2-eq concentrations of 430 to 480 ppm) maintain moderately healthy coral reefs (*medium confidence*). With respect to the RFCs, only the most stringent of scenarios in this category constrain overall risks to unique and threatened systems, and those associated with extreme weather events to a moderate level, while the other scenarios in this category create risk in the high range for these two RFCs. The most stringent among these scenarios constrain the level of risk associated with all other RFCs to the moderate level (*high confidence*). {19.6.3.2-3, 19.7.1}

The higher part of the range of GHG emission scenarios in the literature, that is, those with 2100 CO_2-eq concentrations above 720 ppm create risks associated with extreme weather events and large-scale singular events that are in the high range, and very high range (reflecting inability to adapt) for unique and threatened systems. Risks associated with the distribution of impacts increase toward the very high range (*high confidence*). Risks of global aggregate impacts transition from moderate to high as CO_2-eq concentrations increase from 720 ppm. {19.6.3.2, 19.6.3.4, 19.7.1}

Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable (*very high confidence*). For example, very few integrated assessment model-based scenarios in the literature demonstrate the feasibility of limiting warming to a maximum of 1.5°C with at least 50% likelihood. {19.7.1-2}

The risk of crossing tipping points (critical thresholds) in the Earth system or socio-ecological systems is projected to decrease with reduced GHG emissions {19.7.3}, and the risk of crossing tipping points in socio-ecological systems can also be reduced by reducing human vulnerability or by preserving ecosystem services, or both (*medium confidence*). {19.7.4} The risk of crossing tipping points is reduced by limiting the level of climate change and/or removing concomitant stresses such as overgrazing, overfishing, and pollution, but there is *low confidence* in the level of climate change associated with such tipping points and measures to avoid them.

19.1. Purpose, Scope, and Structure of this Chapter

The objective of this chapter is to assess new literature published since the Fourth Assessment Report (AR4) on emergent risks and key vulnerabilities to climate change from the perspective of the distribution of risk over geographic location, economic sector, time period, and socioeconomic characteristics of individuals and societies. Frameworks used in previous IPCC reports to assess risk in the context of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) are updated and extended in light of new literature, and additional frameworks arising in recent literature are examined. A focal point of this chapter is the interaction of the changing physical characteristics of the climate system with evolving characteristics of socioeconomic and biological systems (exposure and vulnerability) to produce risk (see Figure 19-1). Given the centrality of Article 2 to this chapter, the greater emphasis is on harmful outcomes of climate change rather than potential benefits.

19.1.1. Historical Development of this Chapter

The Third and Fourth Assessment Reports (TAR and AR4, respectively) each devoted chapters to evaluating the state of knowledge relevant to Article 2 of the UNFCCC (Smith et al., 2001; Schneider et al., 2007; see Box 19-1). The TAR sorted and aggregated impacts discussed in the literature according to a framework called Reasons for Concern (RFCs), and assessed the level of risk associated with individual impacts of climate change as well as each category or "reason" as a whole, generally as a function of global mean warming. This assessment took account of the distribution of vulnerability across particular regions, countries, and sectors.

AR4 furthered the discussion relevant to Article 2 by assessing new literature and developing criteria potentially useful for policy makers in the determination of key impacts and vulnerabilities, that is, those meriting particular attention in respect to Article 2. See Box 19-2 for definitions of Reasons for Concern, Key Vulnerabilities (KVs), and related terms. Some definitions go beyond those in the Glossary to provide details especially pertinent to this chapter.

AR4 emphasized the differences in vulnerability between developed and developing countries but also assessed new literature describing vulnerability pertaining to various aggregations of people (such as by ethnic, cultural, age, gender, or income status) and response strategies for avoiding key impacts. The RFCs were updated and the Synthesis Report (IPCC, 2007a) noted that they "remain a viable framework to consider key vulnerabilities" (IPCC, 2007a, Section 5.2). However, their

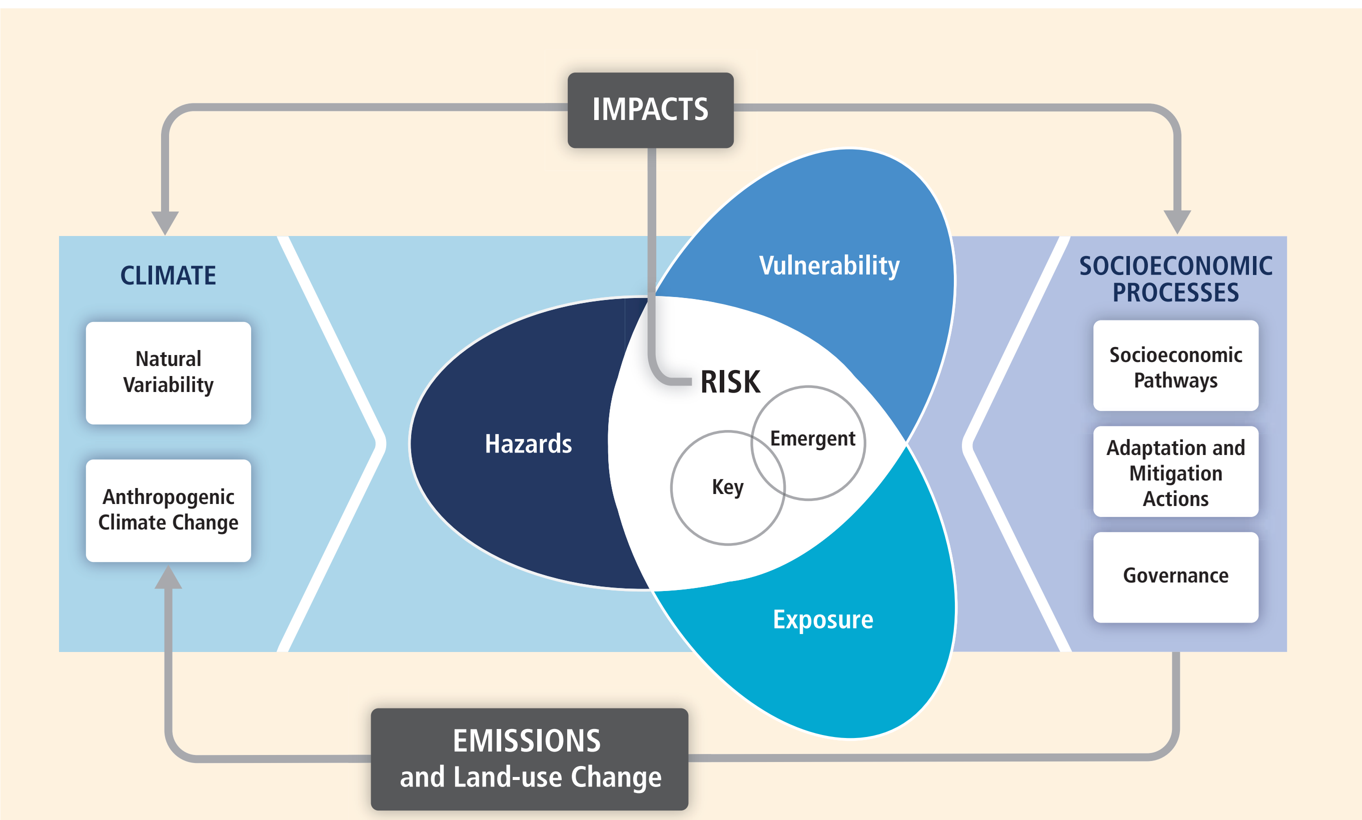

Figure 19-1 | Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. The figure visualizes the different terms and concepts discussed in this chapter. Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. The definition and use of "key" and "emergent" are indicated in Box 19-2 and the Glossary. Vulnerability and exposure are, as the figure shows, largely the result of socioeconomic pathways and societal conditions (although changing hazard patterns also play a role; see Section 19.6.1.1). Changes in both the climate system (left side) and socioeconomic processes (right side) are central drivers of the different core components (vulnerability, exposure, and hazards) that constitute risk (modified version of SREX Figure SPM.1 (IPCC, 2012a)).

utility was limited by several factors: the lack of a time dimension (i.e., representation of impacts arising from timing and rates of climate change and climate forcing); the focus on risk only as a function of global mean temperature; lack of a clear distinction between impacts and vulnerability; and, importantly, incomplete incorporation of the evolving socioeconomic context, particularly adaptation capacity, in representing impacts and vulnerability.

19.1.2. The Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX; IPCC, 2012a) provides additional insights with respect to two RFCs (risks associated with extreme weather events and the distribution of impacts) and particularly the distribution of capacities to adapt to extreme events across countries, communities, and other groups, and the limitations on implementation of these capacities. SREX emphasized the role of the socioeconomic setting and development pathway (expressed through exposure and vulnerability) in determining, on the one hand, the circumstances where extreme events do or do not result in extreme

Box 19-1 | Article 2 of the United Nations Framework Convention on Climate Change

Article 2

OBJECTIVE: The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Frequently Asked Questions

FAQ 19.1 | Does science provide an answer to the question of how much warming is unacceptable?

No. Careful, critical scientific research and assessment can provide information to help society consider what levels of warming or climate change impacts are unacceptable. However, the answer is ultimately a subjective judgment that depends on values and culture, as well as socioeconomic and psychological factors, all of which influence how people perceive risk in general and the risk of climate change in particular. The question of what level of climate change impacts is unacceptable is ultimately not just a matter of the facts, but of how we feel about those facts.

This question is raised in Article 2 of the UNFCCC. The criterion, in the words of Article 2, is "dangerous anthropogenic interference with the climate system"—a framing that invokes both scientific analysis and human values.

Agreements reached by governments since 2009, meeting under the auspices of the UNFCCC, have recognized "the scientific view that the increase in global temperature should be below 2 degrees Celsius" (Section 19.1, UNFCCC, Copenhagen Accord). Still, as informed on the subject as the scientists referred to in this statement may be, theirs is just one valuable perspective. How each country or community will define acceptable or unacceptable levels, essentially deciding what is "dangerous," is a societal judgment.

Science can certainly help society think about what is unacceptable. For example, science can identify how much monetary loss might occur if tropical cyclones grow more intense or heat waves more frequent, or identify the land that might be lost in coastal communities for various levels of higher seas. But "acceptability" depends on how each community values those losses. This question is more complex when loss of life is involved and yet more so when damage to future generations is involved. These are highly emotional and controversial value propositions that science can only inform, not decide.

The purpose of this chapter is to highlight key vulnerabilities and key risks that science has identified; however, it is up to people and governments to determine how the associated impacts should be valued, and whether and how the risks should be acted upon.

Box 19-2 | Definitions

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

A broad set of factors such as wealth, social status, and gender determine vulnerability and exposure to climate-related risk.

Impacts: (Consequences, Outcomes) Effects on natural and human systems. In this report, the term *impacts* is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as *consequences* and *outcomes*. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.

Hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term *hazard* usually refers to climate-related physical events or trends or their physical impacts.

Stressors: Events and trends, often not climate-related, that have an important effect on the system exposed and can increase vulnerability to climate-related risk.

Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur.

Risk = (Probability of Events or Trends) × Consequences

Risk results from the interaction of vulnerability, exposure, and hazard (see Figure 19-1). In this report, the term *risk* is used primarily to refer to the risks of climate-change impacts.

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Key vulnerability, key risk, key impact: A vulnerability, risk, or impact relevant to the definition and elaboration of "dangerous anthropogenic interference (DAI) with the climate system," in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2, meriting particular attention by policymakers in that context.

Key risks are potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate-related hazards with vulnerabilities of societies and systems exposed. Risks are considered "key" due to high hazard or high vulnerability of societies and systems exposed, or both.

Vulnerabilities are considered "key" if they have the potential to combine with hazardous events or trends to result in key risks. Vulnerabilities that have little influence on climate-related risk, for instance, due to lack of exposure to hazards, would not be considered key.

Key impacts are severe consequences for humans and social-ecological systems.

Continued next page →

Box 19-2 (continued)

Extract from WGII AR4 Chapter 19:

Many impacts, vulnerabilities and risks merit particular attention by policy-makers due to characteristics that might make them 'key'. The identification of potential key vulnerabilities is intended to provide guidance to decision-makers for identifying levels and rates of climate change that may be associated with 'dangerous anthropogenic interference' (DAI) with the climate system, in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2 (see Box 19-1). Ultimately, the definition of DAI cannot be based on scientific arguments alone, but involves other judgments informed by the state of scientific knowledge.

Emergent Risk: A risk that arises from the interaction of phenomena in a complex system, for example, the risk caused when geographic shifts in human population in response to climate change lead to increased vulnerability and exposure of populations in the receiving region. Many of the emergent risks discussed in this report have only recently been analyzed in the scientific literature in sufficient detail to permit assessment. In this chapter, the only emergent risks discussed are those that have the potential to become key risks once sufficient understanding accumulates.

Reasons for Concern: Elements of a classification framework, first developed in the IPCC Third Assessment Report, which aims to facilitate judgments about what level of climate change may be "dangerous" (in the language of Article 2 of the UNFCCC) by aggregating impacts, risks, and vulnerabilities.

Summary of Reasons for Concern (revised from WGII TAR Chapter 19; see also Sections 1.2.3, 18.6.4):

"Reasons for Concern" may aid readers in making their own determination about what is a "dangerous" climate change. Each Reason for Concern is consistent with a paradigm that can be used by itself or in combination with other paradigms to help determine what level of climate change is dangerous. The reasons for concern are the relations between global mean temperature increase and:

1. *Risks to unique and threatened systems*
2. *Risks associated with extreme weather events*
3. *Risks associated with the distribution of impacts*
4. *Risks associated with global aggregate impacts*
5. *Risks associated with large-scale singular events*

impacts and disasters, and on the other hand, when non-extreme events may also result in extreme impacts and disasters.

19.1.3. New Developments in this Chapter

With these frameworks already established, and a long list of impacts and key vulnerabilities enumerated and categorized in previous assessments, the current chapter has three goals: first, to recognize and assess risks that arise out of complex interactions involving climate and socio-ecological systems, called *emergent risks* (see Boxes 19-2, CC-KR; Table 19-4). In many cases, scientific literature sufficient to permit assessment of such risks has become available largely since AR4. In this chapter, we consider only those emergent risks that are relevant to interpreting Article 2 or have the potential to become relevant (see criteria in Section 19.2.2) as additional understanding accumulates. For example, since AR4, sufficient literature has emerged to allow initial assessment of the potential relationship between climate change and conflict. The second goal is to reassess and reorganize the existing frameworks (based on RFCs and KVs) for evaluating the literature pertinent to Article 2 of the UNFCCC to address the deficiencies cited in Section 19.1.1, particularly in light of the advances in SREX and the current report's discussions of vulnerability and human security (Chapters 12 and 13) and adaptation (Chapters 14 to 17 and 20). From this perspective, the objective stated in Article 2 may be viewed as aiming in part to ensure human security in the face of climate change. Third, this chapter assesses recent literature pertinent to additional frameworks for categorizing risk and vulnerability, focusing on indirect impacts and interaction and concatenation of risk, including geographic areas of compound risk (Section 19.3).

To clarify the relative roles of characteristics of the physical climate system, such as increases in temperature, precipitation, or storm frequency, and characteristics of the socioeconomic and biological systems with which these interact (vulnerability and exposure) to produce risks of particular consequences (the latter term used interchangeably here with "impacts" and "outcomes"), we rely heavily on a concept used sparingly in the TAR and AR4, *key risks* (see Box 19-2). Furthermore, we emphasize recent literature pointing to the *dynamic* character of vulnerability and exposure based on their intimate relationship to development.

Section 19.2 describes the framework used here for identifying key vulnerabilities, key risks, and emergent risks. We consider a variety of types of emergent risks, including in Section 19.3 those arising from multiple interacting systems and stresses, and in Section 19.4, those arising from indirect impacts, trans-boundary impacts, and impacts occurring at a long distance from the location of the climate change that causes them. One example that illustrates all of these properties is the extent to which climate change impacts on agriculture, water resources, and sea level affect human migration flows. These shifts entail both risks of harm and potential benefits for the migrants, for the regions where they originate, and for the destination regions (see Sections 12.4, 19.4.2.1). Associated risks include indirect impacts, like the effect of land use changes on ecosystems occurring at the new locations of settlement, which may be near the location of the original climate impact or quite distant. Such distant, indirect effects would compound the direct consequences of climate change at the locations receiving the incoming migrants. In Section 19.5, we discuss other risks newly assessed here, including those arising from ocean acidification. Section 19.6 assesses key risks and vulnerabilities in light of the criteria discussed here (Section 19.2.2) and in the context of the RFCs, and Section 19.7 assesses response strategies aimed at avoiding key risks.

19.2. Framework for Identifying Key Vulnerabilities, Key Risks, and Emergent Risks

19.2.1. Risk and Vulnerability

Definitions and frameworks that systematize hazards, exposure, vulnerability, risk, and adaptation in the context of climate change are multiple, overlapping, and often contested (see, e.g., Burton et al., 1983; Blaikie et al., 1994; Twigg, 2001; Turner et al., 2003a,b; UNISDR, 2004; Schröter, 2005; Adger, 2006; Birkmann, 2006b; Füssel and Klein, 2006; Thomalla et al., 2006; Tol and Yohe, 2006; Villagrán de León, 2006; IPCC, 2007a; Cutter and Finch, 2008; Cutter et al., 2008; ICSU-LAC, 2010a,b; Cardona, 2011; DEFRA, 2012; IPCC, 2012a; Kienberger, 2012; Birkmann et al., 2013a; Costa and Kropp, 2013). Today, key reports and most authors differentiate among hazards, vulnerability, risk, and impacts (see, e.g., Hutton et al., 2011; IPCC, 2012a; Birkmann et al., 2013a). The recent literature underscores that risks from climate change are not solely externally generated circumstances or changes in the climate system to which societies respond, but rather the result of complex interactions among societies or communities, ecosystems, and hazards arising from climate change (Susman et al., 1983; Comfort et al., 1999; Birkmann et al., 2011a, 2013a; UNISDR, 2011; IPCC, 2012a). The differentiation of the various aspects of these interactions is an important improvement since AR4 because it exhibits the social construction of risk through the concept of vulnerability (IPCC, 2012a). This new framework, growing out of SREX, translates information more easily into a risk management approach that facilitates policy making (de Sherbinin, 2013). The following section advances this framework in the context of Article 2 of the UNFCCC.

We refer to the characteristics of climate change and its effects on geophysical systems, such as floods, droughts, deglaciation, sea level rise, increasing temperature, and frequency of heat waves, as *hazards*. In contrast, *vulnerability* refers primarily to characteristics of human or social-ecological systems exposed to hazardous climatic (droughts, floods, etc.) or non-climatic events and trends (increasing temperature, sea level rise) (UNDRO, 1980; Cardona, 1986, 1990; Liverman, 1990; Cannon, 1994, 2006; Blaikie et al., 1996; UNISDR, 2004, 2009; Birkmann, 2006a; Füssel and Klein, 2006; Thywissen, 2006; IPCC, 2012a). Ecosystems or geographic areas can be classified as vulnerable, which is of particular concern if human vulnerability increases as a result of potential impairment of the related ecosystem services. The Millennium Ecosystem Assessment (MEA), for example, identified ecosystem services that affect the vulnerability of societies and communities, such as provision of freshwater resources and air quality (Millennium Ecosystem Assessment, 2005a,b). Examples in this chapter and other chapters in this report include the vulnerability of warmwater coral reefs and respective ecosystem services for coastal communities (see Table 19-4; Box CC-KR).

The new framework used here also underscores that the development process of a society has significant implications for exposure, vulnerability, and risk. Climate change is not a risk per se; rather climate changes and related hazards interact with the evolving vulnerability and exposure of systems and therewith determine the changing level of risk (see Figure 19-1; Table 19-4). Identifying key vulnerabilities facilitates estimating key risks when coupled with information about evolving hazards associated with climate change. This approach provides the basis for criteria developed in the following sections.

19.2.2. Criteria for Identifying Key Vulnerabilities and Key Risks

Vulnerability is dynamic and context specific, determined by human behavior and societal organization, which influences for example the susceptibility of people (e.g., by marginalization) and their coping and adaptive capacities to hazards (see IPCC, 2012a). In this regard coping mainly refers to capacities that allow a system to protect itself in the face of adverse consequences, while adaptation—by contrast—denotes a longer term process that also involves adjustments in the system itself and refers to learning, experimentation, and change (Yohe and Tol, 2002; Pelling, 2010; Birkmann et al., 2013a). Perceptions and cognitive constructs about risks and adaptation options as well as cultural contexts influence adaptive capacities and thus vulnerability (Grothmann and Patt, 2005; Rhomberg, 2009; Kuruppu and Liverman, 2011; see Section 19.6.1.4). SREX stressed that the consideration of multiple dimensions (e.g., social, economic, environmental, institutional, cultural), as well as different causal factors of vulnerability, can improve strategies to reduce risks to climate change (see IPCC 2012c, p. 17; Cardona et al., 2012, pp. 17, 67–106).

Key vulnerability and key risk are defined in Box 19-2. Vulnerabilities that have little influence on overall risk are not considered key. Similarly, the magnitude or other characteristics of climate change-related hazards, such as glacier melting, sea level rise, or heat waves, are not by themselves adequate to determine key risks, as the consequences of climate change also will be determined by the vulnerability of the exposed society or social-ecological system. Key vulnerabilities and key risks embody a normative component because different societies might rank the various vulnerability and risk factors and actual or potential types of loss and damage differently (see Schneider et al., 2007, p. 785; Lavell et al., 2012, p. 45). Generally, vulnerability merits particular attention when the survival of societies, communities, or ecosystems is threatened (see UNISDR, 2011, 2013; Birkmann et al., 2011a). Climate change will influence the nature of the climatic hazards people and ecosystems are exposed to and also contribute to deterioration or improvement of coping and adaptive capacities of those exposed to these changes. Consequently, many studies (Wisner et al., 2004; Cardona, 2010; Birkmann et al., 2011a) focus with a priority on the vulnerability of humans and societies as a central feature, rather than solely on the level of climatic change and respective hazards.

19.2.2.1. Criteria for Identifying Key Vulnerabilities

We reorganize and further develop criteria for identifying vulnerabilities as "key" used in AR4 based on the literature (Blaikie et al., 1994; Bohle, 2001; Turner et al., 2003a,b; Birkmann, 2006a, 2011a; Villagrán de León, 2006; Cutter et al., 2008; Cutter and Finch, 2008; ICSU-LAC, 2010a,b; Cardona, 2011; UNISDR, 2011; IPCC, 2012a; Birkmann et al., 2013a) and the differentiation of hazard, exposure, and vulnerability presented here. The criteria in this and succeeding sections were used to identify key vulnerabilities, key risks, and emergent risks in Sections 19.4 and 19.6.1-2, and in Table 19-4. Not all of the criteria need to be fulfilled to characterize a vulnerability or risk as key but the characterization of a phenomenon as a KV or key risk is usually supported by more than one criterion.

The following five criteria are used to judge whether vulnerabilities are key:

1) *Exposure of a society, community, or social-ecological system to climatic stressors*. While exposure is distinct from vulnerability, exposure is an important precondition for considering a specific vulnerability as key. If a system is neither at present nor in the future exposed to hazardous climatic trends or events, its vulnerability to such hazards is not relevant in the current context. Exposure can be assessed based on spatial and temporal dimensions.
2) *Importance of the vulnerable system(s). Views on the importance of different aspects of societies or ecosystems can vary across regions and cultures* (see Kienberger, 2012). However, the identification of KVs is less subjective when it involves characteristics that are crucial for the survival of societies or communities or social-ecological systems exposed to climatic hazards. Defining key vulnerabilities in the context of particular societal groups or ecosystem services also takes into account the conditions that make these population groups or ecosystems highly vulnerable, such as processes of social marginalization or the degradation of ecosystems (Leichenko and O'Brien, 2008; O'Brien et al., 2008; IPCC, 2012a).
3) *Limited ability of societies, communities, or social-ecological systems to cope with and to build adaptive capacities to reduce or limit the adverse consequences of climate-related hazard.* Coping and adaptive capacities are part of the formula that determines vulnerability (see IPCC, 2012a; Birkmann et al., 2013a). While coping describes actions taken within existing constraints to protect the current system and institutional settings, adaptation is a continuous process that encompasses learning and change of the system exposed, including changes of rule systems or modes of governance (Smithers and Smit, 1997; Pielke Jr., 1998; Frankhauser et al., 1999; Smit et al., 1999; Kelly and Adger, 2000; Yohe and Tol, 2002; Adger et al., 2005; Smit and Wandel, 2006; Pelling et al., 2008; Pelling, 2010; Tschakert and Dietrich; 2010; IPCC, 2012a; Birkmann et al., 2013a; Garschagen, 2013). Severe limits of coping and adaptation provide criteria for defining a vulnerability as key, as they are core factors that increase vulnerability to climatic hazards (see, e.g., Warner et al., 2012).
4) *Persistence of vulnerable conditions and degree of irreversibility of consequences.* Vulnerabilities are considered key when they are persistent and difficult to alter. This is particularly the case when the susceptibility is high and coping and adaptive capacities are very low as a result of conditions that are hard to change. Irreversible degradation of ecosystems (e.g., warmwater coral reefs), chronic poverty and marginalization, and insecure land tenure arrangements are drivers of vulnerability that in combination with climatic hazards determine risks that often persist over decades (see Box CC-KR), for example, as observed in the Sahel Zone. In this way, communities or social-ecological systems (e.g., coastal communities dependent on fishing or mountain communities dependent on specific soil conditions) may reach a tipping point (or critical threshold) that would cause a partial or full collapse of the system, including displacement (see Renaud et al., 2010; Section 19.4.2.1). Inability to replace such a system or compensate for potential and actual losses and damages (i.e., irreversibility) is a critical criterion for determining what is "key."
5) *Presence of conditions that make societies highly susceptible to cumulative stressors in complex and multiple-interacting systems*. Conditions that make communities or social-ecological systems highly susceptible to the imposition of additional climatic hazards or that impinge on their ability to cope and adapt, such as violent conflicts (e.g., during drought disaster in Somalia (see Menkhaus, 2010)) are considered under this criterion. Also, the critical dependence of societies on highly interdependent infrastructures (e.g., energy/power supply, transport, and health care) (see Rinaldi et al., 2001; Wang, S. et al., 2012; Atzl and Keller, 2013) leads to key vulnerabilities regarding multiple-interacting systems where capacity to cope or adapt to their failure is low (see Copeland, 2005; Reed et al., 2010; Section 19.6.2.1; Table 19-4).

19.2.2.2. Criteria for Identifying Key Risks

Risks are considered "key" due to high hazard or high vulnerability ("key vulnerability") of societies and systems exposed, or both. Criteria for determining key risks build on the criteria for key vulnerabilities, as vulnerability is a component of risk. As such, risk is strongly determined by coping and adaptive capacities. However, the criteria for identifying key risks also take into account the magnitude, frequency, and intensity of hazardous events and trends linked to climate change to which vulnerable systems are exposed. Accordingly, the following four additional criteria are used to judge whether risks are key:

1) *Magnitude*. Risks are key if associated harmful consequences have a large magnitude, determined by a variety of metrics including human mortality and morbidity, economic loss, losses of cultural importance, and distributional consequences (see Schneider et al., 2007; IPCC, 2012a). Magnitude and frequency of the hazard as well as socioeconomic factors that determine vulnerability and exposure contribute.
2) *Probability that significant risks will materialize and their timing*. Risks are considered key when there is a high probability that the hazard due to climate change will occur under circumstances where societies or social-ecological systems exposed are highly susceptible and have very limited capacities to cope or adapt and consequently potential consequences are severe. Both the timing of the hazard and the dynamics of vulnerability and exposure contribute. Risks that materialize in the near term may be evaluated differently than risks that materialize in the distant future, as the time available for building up adaptive capacities is different (Oppenheimer, 2005; Schneider et al., 2007; see also Section 19.6.3.6).
3) *Irreversibility and persistence of conditions that determine risks*. Persistence of risks refers to the fact that underlying drivers and root causes of these risks, either socioeconomic (e.g., chronic poverty; see Chapter 13) or physical, cannot be rapidly reduced. The criteria for assessing key vulnerabilities include the persistence of socioeconomic conditions contributing to vulnerability that also apply here (Section 19.2.2.1, point 4). In addition, some hazards are associated with the potential for persistent physical impacts, such as loss of an ice sheet causing irreversible sea level rise or release of methane (CH_4) clathrates from the seabed.
4) *Limited ability to reduce the magnitude and frequency or other characteristics of hazardous climatic events and trends and the vulnerability of societies and social-ecological systems exposed*. Criterion 3 pertaining to key vulnerabilities (Section 19.2.2.1) discusses limited ability of societies to improve coping and adaptive capacities in order to manage risk. This criterion also applies here. In addition, risks are also considered to be key when societies together have very limited prospects for reducing the magnitude, frequency, or intensity of the associated climate hazards. For example, risks that may be reduced or limited by greenhouse gas (GHG) reductions that reduce the probability of the associated hazard are less threatening than those for which the likelihood of the hazard cannot be effectively altered (see also Section 19.7.1). For example, risks that are already projected to be large during the next few decades under a range of Representative Concentration Pathways (RCPs) are much more difficult to influence by reducing emissions than those projected to become large late in this century (e.g., see discussion of risk from extreme heat in Section 19.6.3.3).

19.2.3. Criteria for Identifying Emergent Risks

A risk that arises from the interaction of phenomena in a complex system is defined here as an *emergent risk*. For example, feedback processes between climatic change, human interventions involving mitigation and adaptation, and processes in natural systems can be classified as emergent risks if they pose a threat to human security. Emergent risks could arise from unprecedented situations, such as the increasing urbanization of low-lying coastal areas that are exposed to sea level rise or where new pluvial flooding risk emerges due to urbanization of vulnerable areas not historically populated. Some emergent risks have been identified or discussed only recently in the scientific literature, and as a result our ability to assess whether they are key risks is limited. In this chapter, the only emergent risks discussed are those that have the potential to become key risks once sufficient understanding accumulates.

19.2.4. Identifying Key and Emergent Risks under Alternative Development Pathways

Key risks are determined by the interaction of climate-related hazards with exposure and vulnerabilities of societies or ecosystems. Development pathways describing possible trends in demographic, economic, technological, environmental, social, and cultural conditions (Hallegatte et al., 2011) will affect key risks because they influence both the likelihood and nature of climate-related hazards, and the societal and ecological conditions determining exposure and vulnerability. Therefore some risks could be judged to be key under some development pathways but not others. Emergent risks can depend on development pathways as well, because whether or not they become key risks may be contingent on future socioeconomic conditions.

The effect of development pathways on climate-related hazards occurs through their effects on emissions and other radiative forcing factors such as land use change (see WGI AR5 Chapter 12). Components of development pathways such as economic growth, technical change, and policy will influence the rates and spatial distributions of emissions of GHGs and aerosols, and of land use change, and therefore influence the magnitude, timing, and heterogeneity of hazards (see WGIII AR5 Chapter 5).

Development pathways will also influence the factors determining key vulnerabilities of human and ecological systems, including exposure, susceptibility, or sensitivity to impacts, and adaptive capacity (Yohe and Tol, 2002; Füssel and Klein, 2006; Hallegatte et al., 2011; Birkmann et al., 2013a; O'Neill et al., 2014). The magnitude of the aggregate exposure and sensitivity of socio-ecological systems will depend on population growth and spatial distribution, economic development patterns, and social systems. The particular elements of the social-ecological system that are most exposed and sensitive to climate hazards, and that are considered most important, will depend on spatial development patterns as well as on cultural preferences, attitudes toward nature/biodiversity, and reliance on climate-sensitive resources or services, among other factors (Adger, 2006; Füssel, 2009). The degree to which persistent or difficult to reverse vulnerabilities are built into social systems, as well as the degree of inequality in exposure and vulnerability across social groups or regions, also depend on characteristics of development pathways (Adger et al., 2009).

19.2.5. Assessing Key Vulnerabilities and Emergent Risks

The criteria above for assessing vulnerability and risk provide a sequence of potential assessment steps. While the initial assessment phase would explore whether and how a society or social-ecological system is exposed to climate-related hazards, the assessment would subsequently focus on the predisposition of societies or ecosystems to be adversely affected (vulnerability) and the potential occurrence of severe adverse consequences for humans and social-ecological systems once the hazard interacts with the vulnerability of societies and systems exposed. In addition, the importance of the system at risk and the ability of a society or system to cope and to adapt to these stressors would be assessed. Finally, the application of the criteria would also require the assessment of the irreversibility of the consequences and the persistence of vulnerable conditions. Hence, the assessment criteria for risks focus on the internal conditions of a person, a community (e.g., age structure, poverty), or a social-ecological system and the contextual conditions that influence their vulnerability (e.g., governance conditions and systems of norms), in addition to the assessment of hazards, such as storm intensity, heat waves, and sea level rise, which are directly influenced by climate change. Examples of such KVs and key risks drawn from other chapters of this assessment are provided in Section 19.6 and particularly in Table 19-4 and Box CC-KR.

19.3. Emergent Risk: Multiple Interacting Systems and Stresses

19.3.1. Limitations of Previous Approaches Imply Key Risks Overlooked

Interactions of climate change impacts on one sector with changes in exposure and vulnerability, or with adaptation and mitigation actions affecting the same or a different sector, are generally not included or well integrated into projections of risk (Warren, 2011). However, their consideration leads to the identification of a variety of *emergent risks* that were not previously assessed or recognized. This chapter identifies several such complex system interactions that increase vulnerability and risk synergistically (*high confidence*; Section 19.3). There are a very large number of potential interactions, and many important ones have not yet been quantified, meaning that some key risks have been overlooked (*high confidence*). In some cases, literature analyzing these risks is very recent. The six interaction processes listed below, though not exclusive, are systemic and may lead to further key vulnerabilities as well as a larger number of less significant impacts. Several of these are discussed in more detail in the following sections:

- Biodiversity loss induced by climate change that erodes ecosystem services, in turn increasing vulnerability and exposure of human systems dependent on those services (Section 19.3.2.1).
- Alterations in extreme weather events induced by climate change that affect human systems and ecosystems, increasing vulnerability and exposure to the effects of mean climate change. Most impacts projections are based only on changes in mean climate (Rosenzweig and Hillel, 2008; IPCC, 2012a, Box 3-1).
- The interaction between non-climate stressors such as those related to land management, water management, air pollution (which has drivers in common with climate change), and energy production and climate change (Section 19.3.2.2). Heretofore, mainly climate interactions with population/economic growth were assessed.
- Climate changes that increase human exposure and vulnerability to disease (Section 19.3.2.3).
- Locations where risks in different sectors are compounded because impacts, hazards, vulnerability, and exposure interact non-additively (Section 19.3.2.4).
- Mitigation or sectoral adaptation that has unintended consequences for the functioning of another sector (Section 14.6).

19.3.2. Examples of Emergent Risks

19.3.2.1. Emergent Risks Arising from the Effects of Degradation of Ecosystem Services by Climate Change

Biodiversity loss is linked to disruption of ecosystem structure, function, and services (Díaz et al., 2006; Gaston and Fuller, 2008; Cardinale et al., 2012; Maestre et al., 2012; Midgley, 2012). Terrestrial and freshwater species face increased extinction risks under projected climate change during and beyond the 21st century, especially as climate change interacts with other pressures (*high confidence*; Section 4.3.2.5). A large number of modelling studies project that species ranges decline in size as mean climate changes (Section 4.3.2.5); for example, a global scale study of 50,000 species found that the range sizes of 57 ± 6% of widespread and common plants and 34 ± 7% of widespread and common animals are projected to decline by more than 50% by the 2080s if global temperatures increase by 3.5°C relative to preindustrial times, when allowing for species to disperse at observed rates to areas that become newly climatically suitable (Warren et al., 2013a). AR4 (Fischlin et al., 2007, p. 213) estimated that "Approximately 20 to 30% of plant and animal species assessed so far (in an unbiased sample) are likely to be at increasingly high risk of extinction as global mean temperatures exceed a warming of 2 to 3°C above preindustrial levels (*medium confidence*)." Evaluation of various lines of evidence including a range of modeling approaches and, since AR4, new and/or improved techniques (e.g., multifactorial driven species distribution models, species specific population dynamics, tree- and trait-based modeling (for an overview see Bellard et al., 2012, Table 1; also Murray et al., 2011; Dullinger et al., 2012; Staudinger et al., 2012; Foden et al., 2013) imply similar levels of risk as in AR4 with some new estimates indicating higher fractions of species at risk. However, there is *low agreement* on the completeness of these lines of evidence for assigning specific numerical values for fraction of species at risk (see Sections 4.3.2.5, 19.5.1).

These extinction risks and possible declines in species richness are associated with change in mean climate, but ecosystems and species are also expected to be affected by projected climate change-induced increases in short-term extreme weather events and increased fire frequency in some locations (see IPCC, 2012a; WGI AR5 Table SPM.1; WGI AR5 Sections 6.4.8.1, 12.4.3, 12.4.5). Accordingly, despite the recognition of additional uncertainties in numerical estimates since AR4 (Section 4.3.2.5), the evidence for risk to a substantial fraction of species associated with increasing global mean temperature (GMT) is *robust*.

In both terrestrial and marine environments, the potential for the disruption of ecosystem functionality as a result of climate change translates into a key risk of large-scale loss of ecosystem services (Mooney et al., 2009; Midgley, 2012; Table 19-4). At-risk services include water purification by wetlands, removal and sequestration of carbon dioxide (CO_2) by forests, crop pollination by insects, coastal protection by mangroves and coral reefs, regulation of pests and disease, and recycling of waste nutrients (Sections 4.3.4, 22.4.5.6, 27.3.2.1; Box 23-1; Chivian and Bernstein, 2008). Biodiversity loss can lead to an increase in the transmission of infectious diseases such as Lyme, schistosomiasis, and hantavirus in humans, and West Nile virus in birds, creating a newly identified dimension to the emergent risks resulting from biodiversity loss (Keesing et al., 2010).

There are a number of examples of projected yield losses in the agricultural sector due to increased prevalence of pest species under climate change including *Fusarium graminearum* (a fungal disease of wheat), the European corn borer, the Colorado beetle, bakanae disease and leaf blights of rice, and Western corn root worm (Petzoldt and Seaman, 2006; Huang et al., 2010; Kocmánková et al., 2010; Chakraborty and Newton, 2011; Magan et al., 2011; Aragón and Lobo, 2012); or declines in pollinators (Rosenzweig and Hillel, 2008; Abrol, 2012; Bedford et al., 2012; Giannini et al., 2012; Kuhlmann et al., 2012; see also Section 4.3.4). Climate change impacts on pollinators places these valuable services at risk, and affects animals that are dependent on the plants (see Chapter 4). Although the impacts of CO_2 fertilization on plant-pathogen systems is not well understood (Section 7.3.2.3), these processes operate simultaneously with climate change's direct effects on yields through changing temperature, precipitation, and CO_2 concentrations, creating an emergent risk. Climate change has caused, or is projected to cause, range expansion in weeds that have the potential to become invasive (Bradley et al., 2010; Clements and Ditommaso, 2011). These can damage agriculture and threaten other species with extinction, with costs to economies being extremely high (e.g., US$120 billion annually in the USA; Pimentel et al., 2005; Crowl et al., 2008). Although there are also examples of projected decreases in insect damage to crops, there is a tendency for risk of insect damage to plants to increase with climate change (Section 7.3.2.3). Any one of the above mechanisms could result in harmful outcomes that act in synergy with existing climate change impacts on agriculture. Hence, these various susceptibilities to loss of ecosystem services comprise a KV and, in interaction with climate change, imply a potential key risk that global scale yields of a number of crops will be reduced by such interactions.

Severe decline of coral reefs (Section 19.3.2.4) would result in widespread loss of income for many countries, for example, AU$5.4 billion to the Australian economy from tourism (Box CC-CR). More generally, for many small island developing states (SIDS), increases in vulnerability due to loss of such ecosystem services interact with physical impacts of climate change such as sea level rise to create an emergent risk (*high confidence*).

Various studies of ecosystem services, nationally or globally, illustrate the very large values that are attributed to these services (Table 19-1). Such costs are represented only very crudely in aggregate global models of the economic impacts of climate change where "non-market impacts" are estimated very broadly if at all (Section 19.6.3.5). These costs contribute to the large magnitude of risks to human systems resulting from loss of ecosystem services, which in some cases would be irreversible. Hence the increase in vulnerability due to loss of ecosystem services interacting with climate change hazards comprises a key risk (*high confidence*). In some regions (e.g., South America) payment for ecosystem services (PES) has been implemented to support landowners to maintain the provision of services over time (Section 27.6.2; Table 27-7). Studies on degraded ecosystems examine the cost of restoring ecosystem services. Willingness to pay to restore degraded services along the Platte River (USA) (Loomis et al., 2000) greatly exceeded estimated costs of restoration. A meta-analysis of 89 studies looking at the restoration of ecosystem services measured using 526 different metrics found that restoration increased the amount of biodiversity and ecosystem services by 44 and 25% respectively, but restored services were still lower than in intact ecosystems (Benayas et al., 2009). Restoration of damaged ecosystems may be cost-effective, but only partially compensates for loss of services.

Concomitant stress from land use change adds to the extinction risk from climate change, increasing the projected extinction rate (e.g., Şekercioğlu et al., 2012) and contributing to the emergent risk of ecosystem service loss (see also Chapter 4). A synthesis of empirical studies across the globe reveals that ecosystem impacts due to land use change correlate locally with current maximum temperature and recent precipitation decline, indicating a potential for climate change to exacerbate the impacts of land use change (Mantyka-Pringle et al., 2012).

Land clearing releases carbon to the atmosphere and removes carbon sinks (WGI AR5 Section 6.3.2.2) such as old growth forests which would otherwise accumulate carbon (Luyssaert et al., 2008). Studies that value ecosystem services have tended to underestimate the importance of carbon sinks in ecosystems, owing to a tendency to consider only the carbon currently stored in the systems and not the fluxes (Anderson-Teixeira and DeLucia, 2011) and overlooking other aspects such as changes in albedo (e.g., Betts et al., 2012).

19.3.2.2. Emergent Risk Involving Non-Climate Stressors: The Management of Water, Land, and Energy

Human management of water, land, and energy interacts with climate change and its impacts, to profoundly affect risks to the amount of

Table 19-1 | Examples of global and national ecosystem service valuation studies. This table is not intended to be comprehensive. Furthermore, it encompasses studies based on a wide range of methodologies.

Ecosystem service	Region	Value	Currency	Citation
Pollination of crops	Globe	153 billion	Euro	Gallai et al. (2009)
Pollination of crops and wild plants	UK	430 million	£	UK NEA (2011)
Woodland cover increase from 6 to 12%	UK	680 million	£	UK NEA (2011)
CO_2 fixation, O_2 release, nutrient recycling, soil protection, water holding capacity, and environmental purification	Chinese terrestrial ecosystems	6.6 trillion	Yuan RMB	Shi et al. (2012)
Climate regulation provided by forests	USA	1–6 billion	US$ per year	Krieger (2001)
Recreation provided by forests	USA	1.3–110 billion	US$ per year	Krieger (2001)
Biodiversity supported by forests	USA	554 billion	US$ per year	Krieger (2001)
Coral reef services	Australia	5.4 billion	Au$	Section 19.3.2.1; Box CC-CR

carbon that can be stored in terrestrial ecosystems, the amount of water available for use by humans and ecosystems, and the viability of adaptation plans for cities or protected areas. Failure to manage land, water, and energy in a synergistic fashion can exacerbate climate change impacts globally (Searchinger et al., 2008; Wise et al., 2009; Lotze-Campen et al., 2010; Warren et al., 2011) producing emergent risks which are also potential key risks. For example, the use of water by the energy sector, by thermo-electric power generation, hydropower, and geothermal energy, or biofuel production, can contribute to water stress in arid regions (Kelic et al., 2009; Pittock, 2011). Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Box CC-WE; Sections 3.7.2, 7.3.2, 10.2, 10.3.5; McMahon and Price, 2011; Macknick et al., 2012; Ackerman and Fisher, 2013). In irrigated agriculture, climate, crop choice, and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Box CC-WE; Gerten et al., 2011). Recent studies address the energy, water, and land "nexus" to explore risks to the agricultural and energy sectors (Box CC-WE; Tidwell et al., 2011; Skaggs et al., 2012; Smith et al., 2013).

Biofuels can potentially mitigate GHG emissions when used in place of fossil fuels such as gasoline, diesel, and more carbon-intensive fuels from tar sands and heavy oil (Cherubini et al., 2009). One simulation of stringent mitigation (e.g., RCP2.6, which constrains radiative forcing to 2.6 W m^{-2} and therefore limits global mean temperature increase to 2°C over preindustrial levels during the 21st century) shows an increased reliance on biofuels (van Vuuren et al., 2011). However, due to the potential negative consequences of its use as a mitigation strategy, bioenergy development leads to several emergent risks, which are summarized in Table 19-2. Systems that may be vulnerable to bioenergy development are food systems (*high confidence*, due to bioenergy feedstocks replacing food crops; see Table 19-2.iii; Section 19.4.1) and ecosystems (*high confidence*), where biofuel cropping can directly or indirectly induce land use change, displacing terrestrial ecosystems such as forests, which can otherwise also act as carbon sinks (see Table 19-2.i).

While *direct* land use change (LUC) from impacts of biofuel development (from crop substitution and/or biofuel feedstock crop expansion) are a concern, *indirect* land use change (iLUC) has received more attention in the literature—both due to the magnitude of its potential impact (twice as great as direct LUC; Melillo et al., 2009a) and controversy over the uncertainty in accurately quantifying it. iLUC connotes land use change resulting from biofuel impacts on agricultural commodity markets (Fargione et al., 2008; Searchinger et al., 2008). Reductions of GHG emissions from biofuel production and use (compared to fossil fuels) may be offset partly or entirely for decades or centuries from iLUC-induced CO_2 emissions from deforestation and the draining of peatlands (*medium confidence*; Bringezu et al., 2009; van Vuuren et al., 2010; IPCC, 2011, Chapter 2; Miettinen et al., 2012; Smith et al. 2013). In Brazil, further biofuel expansion would be expected to impinge upon the Cerrado, the Amazon, and the Atlantic rainforest—all three of which have high levels of biodiversity (Table 19-2.v) and high levels of endemism (Lapola et al., 2010). Another study of biofuel production in Brazil (Barr et al., 2011) found that when pasture is accounted for, direct expansion into unexploited forest land is minor, that is, most of additional cropland is predicted to come from conversion of pastureland. However, unless the density of livestock operations is increased in tandem, the latter can also lead to iLUC. To the extent that biofuel feedstock crops are grown on areas that were previously fallow or degraded, the iLUC effects might be minimized and CO_2 potentially sequestered (Fargione et al., 2010; IPCC, 2011)—although the amount, alternative uses, and potential productivity of so-called degraded lands are still contested (Dauber et al., 2012). (For more information on the effects of biofuel production on terrestrial ecosystems, see Section 4.4.4; for more information on the effects of land acquisition for biofuel production on the poor, see Section 13.3.1.4.)

Whether such land management dynamics confound or contribute to mitigation depends on important interactions with global emissions mitigation policies (Table 19-2.ii; Van Vuuren et al., 2011). A failure to include land use change emissions within a carbon mitigation regime—for example, by applying a carbon price to fossil fuel and industrial emissions only—has been projected to lead to large-scale deforestation of natural forests and conversion of many other natural ecosystems by the end of the 21st century in 450 ppmv CO_2-eq and 550 ppmv CO_2-eq scenarios (Melillo et al. 2009b; Wise et al., 2009). This dynamic is due primarily to enhanced bioenergy production without a corresponding incentive to limit the resulting land use change emissions. If, instead, an equal carbon price is applied to terrestrial carbon (which, however, presents monitoring difficulties) along with fossil and industrial carbon, deforestation could slow down or even reverse.

That said, there are many equally compelling reasons for a country to encourage biofuel production including a means to produce downward pressure on oil prices, rural development, and reduced oil imports—all of which could be prioritized over biofuels as a GHG mitigation strategy depending on the country (Cherubini et al., 2009). Per-liter GHG emissions from biofuels decrease as agriculture is further intensified through row cropping, fertilizer and pesticide use, and irrigation, while other per-liter environmental impacts such as eutrophication increase (Burney et al., 2010; Grassini and Cassman, 2012). This creates an implicit conflict between alternative development priorities. Second-generation biofuels, such as those based on non-food crops (grasses, algae, timber) and agricultural residues, are expected to offer reduced emissions of GHGs and other air pollutants compared to most first-generation biofuels. This is due primarily to their having a smaller adverse interaction with food systems resulting in less LUC and iLUC (Plevin, 2009; Cherubini and Ulgiati, 2010; Fargione, 2010; Sander and Murthy, 2010). Further, bioelectricity and biogas both may be more effective at mitigating GHG emissions than liquid biofuels (Campbell et al., 2009; Power and Murphy, 2009).

Other emergent risks from bioenergy development are summarized in Table 19-2. Nearly all of the risks presented here are driven by the increased need for raw agricultural feedstocks. Competition for cultivable lands, irrigation resources (Box CC-WE), and other inputs are not unique to biofuel-related issues. The approximate doubling of agricultural demand projected between 2005 and 2050 (Tilman et al., 2011) similarly increases competition for land and water, and would be expected to exacerbate GHG emissions from agriculture (see also WGI AR5 Sections 6.4.3.2, 8.3.5).

Table 19-2 | Emergent risks related to biofuel production as a mitigation strategy.

No.	Issue	Issue description	Nature of emergent risk	Reference
i	Direct and/or indirect land use change	Potential for enhancement of greenhouse gas emissions	Mitigation benefit of biofuels reduced or negated	Melillo et al. (2009a,b); Wise et al. (2009); Khanna et al. (2011)
ii	Policies targeting only fossil carbon	Biofuel cropping competes with agricultural systems and ecosystems for land and water.	Mitigation benefit of policies reduced; harmful interactions with other key systems	Searchinger et al. (2008); Mellilo et al. (2009a,b); Wise et al. (2009); Fargione et al. (2008)
iii	Food/fuel competition for land	Competition for land driving up food prices	Emergent risk of food insecurity due to mitigation-driven land use change	Searchinger et al. (2008); Pimentel et al. (2009); Hertel et al. (2010)
iv	Biofuel production affects water resources.	Competition for water affects biodiversity and food cropping.	Emergent risk of biodiversity loss and food insecurity due to mitigation-driven water stress	Fargione (2010); Fingerman et al. (2010); Poudel et al. (2012); Yang et al. (2012)
v	Biofuel production affects biodiversity.	Competition for land reduces natural forest and biodiversity.	Emerging risk of biodiversity loss due to mitigation-driven land use change	Fizherbert et al. (2008); Koh et al. (2009); Lapola et al. (2010); Fletcher et al. (2011)
vi	Land conversion causes air pollution.	Potential for increased production of tropospheric ozone from palm/sugarcane-induced land use change	Emergent risk of greenhouse gas-mitigation-driven plant and human health damage caused by tropospheric ozone	Cançado et al. (2006); Hewitt et al. (2009)
vii	Fertilizer application	Potential for increased emissions of N_2O	Offsets some benefits of other mitigation measures	Donner and Kucharik (2008); Searchinger et al. (2008); Fargione (2010)
viii	Invasive properties of biofuel crops	Potential to become an invasive species	Unintended consequences that damage agriculture and/or biodiversity	Raghu et al. (2006); DiTomaso et al. (2007); Barney and Ditomaso (2008)

Projected changes in the hydrological cycle due to climate change (WGI AR5 Section 12.4.5) combined with increasing water demand leads to an emergent, potentially key risk of water stress exacerbated by the reduction of groundwater which serves as "an historical buffer against climate variability" (Green et al., 2011), and potentially further exacerbated by existing governance constraints that can act as barriers to reduce vulnerability. Climate change and increasing food demand are expected to drive expansion of irrigated cropland (Wada et al., 2013), increasing the demand for energy intensive extraction and conveyance of (ground or desalinated sea) water for irrigation (see Box CC-WE). If water is provided through groundwater extraction, pumping, or construction and use of de-salinization plants, local energy demand (and GHG emissions) will increase, although advanced irrigation systems are available that minimize enhancement of emissions (Rothausen and Conway, 2011).

A further potential key risk arises from increased water stress due to unsustainable groundwater extraction, which is expected to increase as an adaptation to climate change. Groundwater extraction is generally increasing globally with particularly large extraction in India and China (Wang, J. et al., 2012). The effects of climate change on groundwater are varied with some areas expecting decreased recharge while others are projected to experience increased recharge (Green et al., 2011; Portmann et al., 2013). Where extraction rates increase or recharge decreases, water tables will be depleted with potential key risks to local ecosystems and human systems (such as agriculture, tourism, and recreation), while water quality will decrease. One projection shows insufficient water availability in Africa, Latin America, and the Caribbean to satisfy both agricultural demands and ideal environmental flow regulations for rivers by 2050, a situation that is exacerbated by climate change (Strzepek and Boehlert, 2010).

19.3.2.3. Emergent Risks Involving Health Effects

Climate change will act through numerous direct and indirect pathways to alter the prevalence and distribution of diseases that are climate and weather sensitive. These effects will differ substantially depending on baseline epidemiologic profiles, reflecting the level of development and access to clean and plentiful water, food, and adequate sanitation and health care resources. Furthermore, the impact of climate change will differ within and between regions, depending on the adaptive capacity of public health and medical services and key infrastructure that ensures access to clean food and water.

A principal emergent global public health risk is malnutrition secondary to ecological changes and disruptions in food production as a result of changing rainfall patterns, increases in extreme temperatures (*high confidence*; IPCC, 2012a; see also Section 11.6.1), and increased atmospheric CO_2 (Taub et al., 2008; Burke and Lobell, 2010; Section 7.3.2.5). Modeling of the magnitude of the effect of climate change on future under-nutrition in five regions in South Asia and sub-Saharan Africa in 2050 (using *Special Report on Emissions Scenarios* (SRES) A2 emissions scenario) suggests an increase in moderate nutritional stunting, an indicator linked to increased risk of death and poor health (Black et al., 2008), of 1 to 29%, depending of the region assessed, compared to a future without climate change, and a much greater impact on severe stunting for particular regions, such as 23% for central sub-Saharan Africa and 62% for south Asia (Lloyd et al., 2011). The impact of climate-induced drought and precipitation changes in Mali include the southward movement of drought-prone areas which would result in a loss of critical agriculturally productive land by 2025 and increase food insecurity (Jankowska et al., 2012).

In densely populated megacities, especially those with a pronounced urban heat island effect, a principal emergent health risk results from the synergistic interaction between increased exposure to extreme heat and degraded air quality with the convergence of increasing vulnerability of an aging population and a global shift to urbanization (*high confidence*; Sections 8.2.3.5, 8.2.4.6, 11.5.3; Box CC-HS). These trends will increase the risk of relatively higher mortality from exposure to excessive heat (Knowlton et al., 2007; Kovats and Hajat, 2008; Luber and McGeehin, 2008). The health risks of such interactions include increased injuries and fatalities as a result of severe weather events including heat waves (see Section 19.6.3.3); increased aeroallergen production in urban areas leading to increases in allergic airway diseases (see Section 19.5.3); and respiratory and cardiovascular morbidity and mortality secondary to degraded air quality and ozone formation (see Section 19.6.3.3). While the association between ambient air quality and health is well established, there is an increasingly *robust* body of evidence linking spikes in respiratory diseases to weather events and to climate change. In New York City, for example, each single degree (Celsius) increase in summertime surface temperature has been associated with a 2.7–3.1% increase in same-day hospitalizations due to respiratory diseases, and an increase of 1.4–3.6% in hospitalizations due to cardiovascular diseases (Lin et al., 2009). Respiratory health outcomes will be exacerbated by climate change through increased production and exposure to ground-level ozone (particularly in urban areas), wildfire smoke, and increased production of pollen (D'Amato et al., 2010).

19.3.2.4. Spatial Convergence of Multiple Impacts: Areas of Compound Risk

In this chapter, we define an area of compound risk as a region where climate change-induced impacts in one sector affects other sectors in the same region, or a region where climate change impacts in different sectors are compounded, resulting in extreme or high-risk consequences. The frequent and ongoing spatial and temporal coincidence of impacts in different sectors in the same region has consequences that are more serious than simple summation of the sectoral impacts indicates (*medium confidence*). Such synergistic processes are difficult to identify through sectoral assessment and are apt to be overlooked in spite of their potential importance in considering key vulnerabilities and risks. For example, a large flood in a rural area may damage crop fields severely, causing food shortages (Stover and Vinck, 2008). The flood may simultaneously cause a deterioration of hygiene in the region and the spread of water-borne diseases (Schnitzler et al., 2007; Hashizume et al., 2008; Kovats and Akhtar, 2008). The coincidence of disease and malnutrition can thus create an area of compound risk for health impacts, with the elderly and children most at risk.

As a systematic approach, identification of areas of compound risk could be achieved by overlaying spatial data of impacts in multiple sectors, but this cannot indicate synergistic influences and dynamic changes in these influences quantitatively. For global analysis, certain types of integrated assessment models that allow spatial analysis of climate change impacts have been used to identify regions that are affected disproportionately by climate change (MNP, 2006; Kainuma et al., 2007; Warren et al., 2008; Füssel, 2010). Recent efforts attempt to collect and archive spatial data on impact projections and facilitate their public use. These have created overlays for identifying areas of compound risk with Web-Geographic Information Systems (GIS) technology (Adaptation Atlas; Resources for the Future, 2009). There are also efforts to coordinate impacts assessments adopting identical future climatic and/or socioeconomic scenarios at various spatial scales (Parry et al., 2004; Piontek et al., 2014). Areas of compound risk identified by overlaying spatial data of impacts in multiple sectors can be used as a starting point for regional case studies on vulnerability and multifaceted adaptation strategies (Piontek et al., 2014).

Frequently Asked Questions

FAQ 19.2 | How does climate change interact with and amplify preexisting risks?

There are two components of risk: the probability of adverse events occurring and the impact or consequences of those events. Climate change increases the probability of several types of harmful events that societies and ecosystems already face, as well as the associated risks. For example, people in many regions have long faced threats associated with weather-related events such as extreme temperatures and heavy precipitation (which can trigger flooding). Climate change will increase the likelihood of these two types of extremes as well as others. Climate change means that impacts already affecting coastal areas, such as erosion and loss of property in damaging storms, will become more extensive due to sea level rise. In many areas, climate change increases the already high risks to people living in poverty or to people suffering from food insecurity or inadequate water supplies. Finally, climate and weather already pose risks for a wide range of economic sectors, including agriculture, fisheries, and forestry: climate change increases these risks for much of the world.

Climate change can amplify risks in many ways, including through indirect interactions with other risks. These are often not considered in projections of climate change impacts. For example, hotter weather contributes to increased amounts of ground level ozone (smog) in polluted areas, exacerbating an existing threat to human health, particularly for the elderly and the very young and those already in poor health. Also, efforts to mitigate or adapt to climate change can have negative as well as positive effects. For example, government policies encouraging expansion of biofuel production from maize have recently contributed to higher food prices for many, increasing food insecurity for populations already at risk, and threatening the livelihoods of those like the urban poor who are struggling with the inherent risks of poverty. Increased tapping of water resources for crop irrigation in one region in response to water shortages related to climate change can increase risks to adjacent areas that share those water resources. Climate change impacts can also reverberate by damaging critical infrastructure such as power generation, transportation, or health care systems.

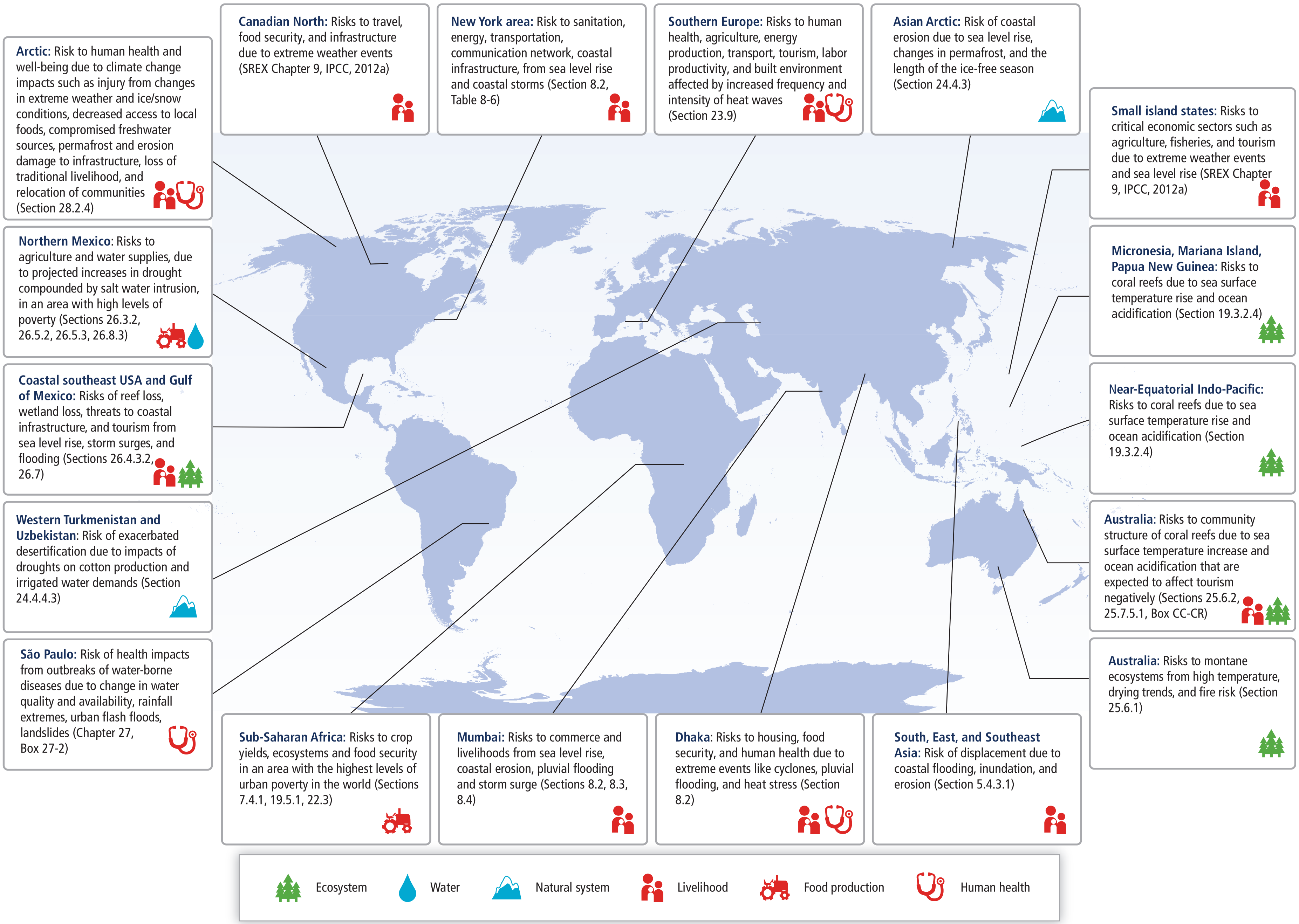

Figure 19-2 | Some examples of areas of compound risk identified in this assessment. Symbols indicate one or two of the main sectors or systems subject to compound risk, but in each case additional sectors and systems are at risk.

General equilibrium economic models (see Chapter 10) may facilitate quantitative evaluation of synergistic influences. An analysis of the EU by the PESETA project (Projections of economic impacts of climate change in sectors of Europe based on bottom-up analysis) showed sub-regional welfare loss by considering impacts on agriculture, coastal system, river floods, and tourism together in the Computable General Equilibrium (CGE) model, which is designed to represent interrelationships among economic activities of sectors. The result indicated the largest percentage loss in southern Europe (Ciscar et al., 2011).

The following examples illustrate different types of areas of compound risk where climate change impacts coincide and interact:

1) *Cities in deltas*, which are subject to sea level rise, storm surge, coastal erosion, saline intrusion, and flooding. Extreme weather events can also disrupt access to food supplies, enhancing malnutrition risk (Ahmed et al., 2009; see also Section 19.3.2.3). Based on national population projections, if contemporary rates of effective sea level rise (a net rate, defined by the combination of eustatic sea level rise and local contributions from fluvial sediment deposition and subsidence and subsidence due to groundwater and hydrocarbon extraction) continue through 2050, more than 6 million people would be at risk of enhanced inundation and increased coastal erosion in three megadeltas and 8.7 million in 40 deltas, absent measures to adapt (Ericson et al., 2006). Examples of urbanized delta areas at risk include, for example, those where Mumbai and Dhaka are located (see Chapters 8, 24; Section 19.6.3.4; Table 19-4).
2) *The Arctic*, where indigenous people (Crowley, 2011) are projected to be exposed to the disruption, and possible destruction of, their hunting and food sharing culture (see Chapter 28). Risk arises from a combination of sea ice loss and the concomitant local extinctions of the animals dependent on the ice (Johannessen and Miles, 2011). Thawing ground also disrupts land transportation, buildings, and infrastructure while exposure of coastal settlements to storms also increases due to loss of sea ice. Arctic ecosystems are broadly at risk (Kittel et al., 2011).
3) *Coral reefs*, which are highly threatened due to the synergistic effects of sea surface temperature rise and perturbed ocean chemistry, reducing calcification and also increasing sensitivity to other impacts such as the loss of coral symbionts (Chapter 6). The importance of reef sensitivity to climate change was recently highlighted in the near-equatorial Indo Pacific, the area of greatest reef diversity worldwide (Lough, 2012). A second highly diverse reef system at risk for warming was identified around Micronesia, Mariana Island, and Papua New Guinea (Meissner et al., 2012).

In Figure 19-2, these and other examples of areas of compound risk identified in this assessment are indicated on a world map. The map focuses on the key role that exposure plays in determining risk, particularly compound risk, rather than vulnerabilities per se.

19.4. Emergent Risk: Indirect, Trans-boundary, and Long-Distance Impacts

Climate change impacts can have consequences beyond the regions in which they occur. Global trade systems transmit and mediate a variety of impacts—the most prominent example of this is the global food trade system. The competitive market forces which dominate trade do not account for considerations of justice, and thus can incidentally diminish or enhance inequality in the distribution of impacts (see Section 19.6.3.4). Where prices on food, land, and other resources increase, vulnerability increases, *ceteris paribus*, for those most in need and least able to pay (see Section 19.6.1.2 on differential vulnerability). In addition, both mitigation and other adaptation responses have unintended consequences beyond the locations in which they are implemented (Oppenheimer, 2013). All of these mechanisms can create emergent risks (*high confidence*).

19.4.1. Crop Production, Prices, and Risk of Increased Food Insecurity

Recent literature indicates that climate trends have already influenced the yield trends of important crops (e.g., Kucharik and Serbin, 2008; Tao et al., 2008; Brisson et al., 2010; Lobell et al., 2011). Chapters 7 and 18 provide a detailed overview of these impacts, and have assessed with *medium confidence* that the effects of climate trends on maize and wheat yield trends have been negative in many regions over the past several decades, and have been small for major rice and soybean production areas (see Sections 7.2.1.1, 18.4.1.1.). For projected impacts, "Without adaptation, local temperature increases in excess of about 1°C above preindustrial is projected to have negative effects on yields for the major crops (wheat, rice, and maize) in both tropical and temperate regions, although individual locations may benefit (*medium confidence*)" (Section 7.4; Figures 7-4, 7-5, 7-7; Chapter 7 ES). Across all studies projecting crop yield impacts (some of which include both CO_2 fertilization and adaptation, and some which account for only one or neither of these), negative impacts on average yields become *likely* from the 2030s (Figure 7-5). Median yield impacts of 0 to –2% per decade are projected for the rest of the century (compared to yields without climate change) (Figure 7-7), and after 2050 the risk of more severe impacts increases (*medium confidence*) (Chapter 7 ES; Figure 7-5). Among the smaller number of studies that have projected global yield and price impacts, negative net effects of climate change, CO_2 increases, and agronomic adaptation on global yields are *about as likely as not* by 2050 and *likely* later in the 21st century (Section 7.4.4).

Climate impacts on crop production influence food prices directly and through complex interactions with a variety of factors, including biofuel crop production and mandates, as well as other domestic policies such as crop export bans (Sections 7.1.2, 7.2.2, 7.4.4). If climate changes reduce crop yields, international food prices and the number of food-insecure people are expected to increase globally (*limited evidence*, *high agreement*; Section 7.4.4). For example, global rice prices exhibit sensitivity both to yield impacts from climate changes as well as the loss of arable land to sea level rise (Chen et al., 2012). While the evidence base of how climate change will affect future food consumption patterns is limited (Section 7.3.3.2), there are large numbers of households that would be especially vulnerable to a loss of food access if food prices were to increase, for example, agricultural producers in low-income countries who are net food buyers (Section 7.3.3.2; Table 7-1).

In addition to the direct impacts of climate change, biofuel production in service of climate change mitigation may also affect food prices.

Accurately tracking and quantifying the direct and indirect impacts of biofuel production on the food system has become an intense area of study since AR4. U.S. ethanol production (for which maize is the primary feedstock) increased around 720% since 2000, with maize commodity prices nearly tripling and harvested land growing by more than 10%, mainly at the expense of soy (Wallander et al., 2011; EIA, 2013). Ethanol recently consumed one-quarter of U.S. maize production, even after accounting for feed by-products returned to the market (USDA, 2013). However, isolating biofuels' exact contribution to food system changes from other factors such as extreme weather events, climate change, changing diets, and increasing population have proven difficult (Zilberman et al., 2011). Still, estimates of the supply and demand elasticity of basic grain commodities lead to a prediction that the 2009 U.S. Renewable Fuel standard could increase commodity prices of maize, wheat, rice, and soybeans by roughly 20%, *ceteris paribus*, assuming one-third of the calories used in ethanol production can be recycled as animal feed (Roberts and Schlenker, 2013). More generally, there is *high confidence* that pressure on land use for biofuels will further increase food prices (see Table 19-2.iii).

In summary, through the global food trade system, climate change impacts on agriculture can have consequences beyond the regions in which those impacts are directly felt. Food access can be inhibited by rising food price levels and volatility (Sections 7.3.3.1-2), as demonstrated during the recent 2007–2008 price rise episode that resulted from the combination of poor weather in certain world regions combined with a demand for biofuel feedstocks, increased demand for grain-fed meat, and historically low levels of food stocks (Abbot and Borot de Battisti, 2011; Adam and Ajakaiye, 2011; Figure 7-3). These episodes provide an analog elucidating how reduced crop yields due to impacts of climate variability and biofuel cropping work synergistically to create a risk of increased food insecurity: hence this interaction of climate change and mitigation actions with the food system via markets comprises an *emergent risk* of the impacts of climate change acting at a distance, affecting the food security of vulnerable households (Section 7.3.3.2).

19.4.2. Indirect, Trans-boundary, and Long-Distance Impacts of Adaptation

Risk can also arise from unintended consequences of adaptation (see Section 14.6), and this can act across distance, if for example, there is migration of people or species from one region to another. Adaptation responses in human systems can include land use change, which can have both trans-boundary and long-distance effects, and changes in water management, which often has downstream consequences.

19.4.2.1. Risks Associated with Human Migration and Displacement

Human migration is one of many possible adaptive strategies or responses to climate change (Reuveny, 2007; Tacoli, 2009; Piguet, 2010; McLeman, 2011), assessed in detail in Chapter 12 in the context of the many other causes of migration. Displacement refers to situations where choices are limited and movement is more or less compelled by land loss due to sea level rise or extreme drought, for example (see Section 12.4). A number of studies have linked past climate variability to both local and long-distance migration (see review by Lilleør and Van den Broeck, 2011). In addition to yielding positive and negative outcomes for the migrants, migration indirectly transmits consequences of climate variability and change at one location to people and states in the regions receiving migrants, sometimes at long distances. Consequences for receiving regions, which can be assessed by a variety of metrics, could be both positive and negative, as may also be the case for sending regions (Foresight, 2011; McLeman, 2011; see Chapter 12). A rapidly growing literature examines potential changes in migration patterns due to future climate changes, but projections of specific positive or negative outcomes are not available. Furthermore, recent literature underscores risks previously ignored: risks arising from the lack of mobility in face of a changing climate, and risks entailed by those migrating into areas of direct climate-related risk, such as low-lying coastal deltas (Foresight, 2011; see Section 12.4.1.2).

Climate change-induced sea level rise, in conjunction with storm surges and flooding, creates a threat of temporary and eventually permanent displacement from low-lying coastal areas, the latter particularly the case for small island developing states (SIDS) and other small islands (Pelling and Uitto 2001; see Chapter 12). The distance and permanence of the displacement will depend on whether governments develop strategies such as relocating people from highly vulnerable to less vulnerable areas nearby, and conserving ecosystem services which provide storm surge protection in addition to so-called "hardening" including building sea walls and surge barriers (Perch-Nielsen, 2004; Box CC-EA). Numbers of people at risk from coastal land loss have been estimated on a regional basis (Ericson et al., 2006; Nicholls and Tol, 2006; Nicholls et al., 2011) yet projections of resulting anticipatory migration or permanent versus temporary displacement are not available.

Taken together, these studies indicate that climate change will bear significant consequences for migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states (*high confidence*). Urbanization is a pervasive aspect of recent migration which brings benefits but, in the climate change context, also significant risks (see Sections 8.2.2.4, 19.2.3, 19.6.1-2, 19.6.3.3). While the literature projecting climate-driven migration has grown recently (Section 12.4), there is as of yet insufficient literature to permit assessment of projected region-specific consequences of such migration. Nevertheless, the potential for negative outcomes from migration in such complex, interactive situations is an emergent risk of climate change, with the potential to become a key risk (Box CC-KR).

19.4.2.2. Risk of Conflict and Insecurity

Violent conflict between individuals or groups arises for a variety of reasons (Section 12.5). Factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change and variability (*high confidence*; Sections 12.5.1, 12.5.3, 13.2). In this section, we focus on evidence for the magnitude of a climate effect on violent conflict to assess its potential to become a key risk.

The only meta-analysis of the literature (Hsiang et al., 2013), examining 60 quantitative empirical studies generally published since AR4, implicates climatic events as a contributing factor to the onset or intensification of several types of personal violence, group conflict, and social instability in contexts around the world, at temporal scales ranging from a climatologically anomalous hour to an anomalous millennium and at spatial scales ranging from the individual level (Vrij et al., 1994; Ranson, 2012) to the communal level (Hidalgo et al., 2010; O'Loughlin et al., 2012) to the national level (Burke et al., 2009; Dell et al., 2012) to the global level (Hsiang et al., 2011). Nevertheless, some individual studies have been unable to obtain evidence that violence has a statistically significant association with climate (Buhaug, 2010; Theisen et al., 2011). In detection and attribution of their impact on human conflict, there is *low confidence* that climate change has an effect (Section 18.4.5) and *medium confidence* that climate variability has an effect.

Evidence suggests that climatic events over a large range of time and spatial scales contribute to the likelihood of violence through multiple pathways discussed in Section 12.5 (Bernauer et al., 2012; Scheffran et al., 2012; Hsiang and Burke, 2014). Results from modern contexts (1950–2010) indicate that the frequency of violence between individuals rises 2.3% and the frequency of intergroup conflict rises 13.2% for each standard deviation change toward warmer temperatures (Hsiang et al., 2013). Because annual temperatures around the world are expected to rise 2 to 4 standard deviations (as measured over 1950–2008) above temperatures in 2000 by 2050 (A1B scenario) (Hsiang et al., 2013), there is potential *ceteris paribus* for large relative changes to global patterns of personal violence, group conflict, and social instability in the future.

Social, economic, technological, and political changes that might exacerbate or mitigate this potential impact are discussed in Chapter 12. These changes may cause future populations to respond to their climate differently than modern populations; however, the influence of climate variability on rates of conflict is sufficiently large in magnitude that such advances may need to be dramatic to offset the potential influence of future climate changes.

The effect of climate change on conflict and insecurity has the potential to become a key risk because factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change (*medium confidence*; Sections 12.5.1, 12.5.3, 13.2), and in numerous statistical studies the influence of climate variability on human conflict is large in magnitude (*medium confidence*).

19.4.2.3. Risks Associated with Species Range Shifts

One of the primary ways species adapt to climate change is by moving to more climatically suitable areas (range shifts). These shifts will affect ecosystem functioning, potentially posing risks to ecosystem services (*medium confidence*; Millennium Ecosystem Assessment, 2005a,b; Dossena et al., 2012), including those related to climate regulation and carbon storage (Wardle et al., 2011). One example of a key impact is the warming-driven expansion and intensification of Mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in North American pine forests and its current and projected impacts on carbon regulation and economies (Sections 26.4.2.1, 26.8.3). Risks also arise from projected range shifts of important resource species (e.g., marine fishes; Sections 6.5.2-3), as well as from potential introductions of diseases to people, livestock, crops, and native species (see Sections 5.4.3.5, 7.3.2.3, 22.3.5, 23.4.2, 26.6.1.6, 28.2.3). Many newly arrived species prey on, outcompete, or hybridize with existing biota (e.g., by becoming weeds or pests in agricultural systems) (Section 4.2.4.6) . The ecological implications of species reshuffling into novel, no-analog communities largely remain unknown and pose additional risks that cannot yet be assessed (Root and Schneider, 2006; Sections 6.5.3, 19.5.1, 21.4.3).

Current legal frameworks and conservation strategies face the challenge of untangling desirable species range shifts from undesirable invasions (Webber and Scott, 2012), and identifying circumstances when movement should be facilitated versus inhibited. New agreements may be needed recognizing climate change impacts on existing, new, or altered trans-boundary migration (e.g., under the Convention on the Conservation of Migratory Species of Wild Animals). As target species and ecosystems move, protected area networks may become less effective, necessitating re-evaluation and adaptation, including possible addition of sites, particularly those important as either "refugia" or migration corridors (Warren et al., 2013a; Sections 9.4.3.3, 24.4.2.5, 24.5.1). Assisted colonization—moving individuals or populations from currently occupied areas to locations with higher probability of future persistence—is arising as a potential conservation tool for species unable to track changing climates (Sections 4.4.2.4, 21.4.3). The value of these approaches, however, is contested and implementation is very limited giving *low confidence* that this would be an effective technique (Loss et al., 2011). *Ex situ* collections (Section 4.4.2.5) have often been put forward as fallback resources for conserving threatened species, yet the expense and the relatively low representation of global species and genetic diversity (Balmford et al., 2011; Conde et al., 2011) minimize the effectiveness of this technique.

19.4.3. Indirect, Trans-boundary, and Long-Distance Impacts of Mitigation Measures

Mitigation, too, can have unintended consequences beyond its boundaries, which may affect natural systems and/or human systems. If mitigation involves a form of land use change, then regional implications can ensue in the same way as they can for adaptation (see Section 14.7).

Mitigation can potentially reduce direct climate change impacts on biodiversity (Warren et al., 2013a). However, impacts on biodiversity as a result of land use change induced by biofuel production can offset benefits associated with biofuels (see Boxes 4-1, 25-10; Sections 4.2.4.1, 4.4.4, 9.3.3.4, 19.3.2.2, 22.6.3, 24.6, 27.2.2.1). Climate change mitigation through "clean energy" substitution can also have negative impacts on biodiversity. However, attention to siting and monitoring can decrease some negative ecological and socioeconomic impacts (*medium confidence*) while maximizing positive ones (Section 4.4.4). For example, the U.S. Government performed an intensive study of suitable sites for solar power on public lands in the western USA. The end result opened 285,000 acres of public land for large-scale solar deployment while blocking development on 78 million acres to protect "natural and cultural" resources (US DOE and BLM, 2012). The construction of large hydroelectric dams can affect both terrestrial and aquatic ecosystems

Frequently Asked Questions

FAQ 19.3 | How can climate change impacts on one region cause impacts on other distant areas?

People and societies are interconnected in many ways. Changes in one area can have ripple effects around the world through globally linked systems such as the economy. Globalized food trade means that changed crop productivity as a result of extreme weather events or adverse climate trends in one area can shift food prices and food availability for a given commodity worldwide. Depletion of fish stocks in one region due to ocean temperature rise can cause impacts on the price of fish everywhere. Severe weather in one area that interferes with transportation or shipping of raw or finished goods, such as refined oil, can have wider economic impacts.

In addition to triggering impacts via globally linked systems like markets, climate change can alter the movement of people, other species, and physical materials across the landscape, generating secondary impacts in places far removed from where these particular direct impacts of climate change occur. For example, climate change can create stresses in one area that prompt some human populations to migrate to adjacent or distant areas. Migration can affect many aspects of the regions people leave, as well as many aspects of their destination points, including income levels, land use, and the availability of natural resources, and the health and security of the affected populations—these effects can be positive or negative. In addition to these indirect impacts, all regions experience the direct impacts of climate change.

along river systems (World Commission on Dams, 2000; see also Sections 3.7.2.1, 4.4.4, 24.4.2.3, 24.9.1).

Mitigation strategies will have a range of effects on human systems. Reforestation that properly mimics existing forest ecosystems in structure and composition would potentially benefit human systems by stabilizing micro-climatic variation (Canadell and Raupach, 2008) and allowing benefits from the sustainable harvest of non-timber forest products for food, medicine, and other marketable commodities (Guariguata et al., 2010). However, there is a generally longer time frame and greater expense involved in recreating a diverse forest system. Afforestation creates a similar set of costs and benefits (Sections 3.7.2.1, 4.4.3, 17.2.7.1, 22.4.5.6-7; Box CC-WE). Mitigation strategies designed to reduce dependence on carbon-intensive fuels present a very different set of circumstances in relation to human systems. The development of bioresources for energy use may have significant economic and market effects potentially influencing food prices (see also Section 19.4.1). This would especially affect populations that already devote a considerable portion of their household income to food (Hymans and Shapiro, 1976).

19.5. Newly Assessed Risks

Newly assessed risks are those for which the evidence base in the scientific literature has only recently become sufficient to allow for assessment. Furthermore, these risks have at least the potential to become key based on the criteria in Section 19.2.2. Several of the emergent risks discussed in Sections 19.3 and 19.4, including those associated with human migration (Section 19.4.2.1) and mitigation measures (Section 19.4. 3), can be considered newly assessed. Others are related to diverse aspects of climate change, including the impacts of a large temperature rise, ocean acidification and other direct consequences of CO2 increases, and the potential impacts of geoengineering implemented as a climate change response strategy.

19.5.1. Risks from Large Global Temperature Rise >4°C above Preindustrial Levels

Most climate change impact studies focus on climate change scenarios corresponding to global mean temperature rises of up to 3.5°C relative to 1990 (slightly more than 4°C above preindustrial levels), with only a few examples of assessments of temperature rise significantly above that level (Parry et al., 2004; Hare, 2006; Warren et al., 2006; Easterling et al., 2007; Fischlin et al., 2007). Recently the potential for larger amounts of warming has received increasing attention and preliminary assessment of impacts above that level of warming is possible for agriculture, ecosystems, water, health, and large-scale singular events. In this section, all temperature changes are global and relative to preindustrial levels. Relevant climate scenarios include those based on RCP8.5, which in 2081–2100 is projected to result in a temperature rise of 4.3°C ± 0.7°C with temperature above 4°C *as likely as not* (WGI AR5 Section 12.4.1, Table 12.3), and some simulations using SRES A2 and A1FI, which can reach 5.9°C and 6.9°C warming, respectively, by 2100 (WGI AR4 SPM). Literature that uses these scenarios but assumes low climate sensitivity and hence less than 4°C of warming is excluded.

Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more (Section 7.4.1). Among these, one indicates substantial reductions in yields in sub-Saharan Africa (Thornton et al., 2011) and another indicates reversal of gains in yields and substantial reductions for Finland (Rötter et al., 2011). Other studies at or below 4 °C anticipate yield losses, particularly in tropical regions, even when taking agronomic adaptations into account (Section 7.5.1.1.1). The possibility of compensation for these losses due to other responses of the food system to impacts on production, such as land use change and adjustment of trade patterns, cannot yet be adequately assessed for a world with GMT >4°C (Sections 19.4.1, 19.6.3.4).

Assessments of ecological impacts at and above 4°C warming imply a high risk of extensive loss of biodiversity with concomitant loss of ecosystem services (*high confidence*; Section 4.3.2.5; Table 4-3). AR4 estimated that 20 to 30% of species were likely at increasingly high risk of extinction as global mean temperatures exceed a warming of 2°C to 3°C above preindustrial levels (*medium confidence*; Fischlin et al., 2007); hence 4°C warming implies further increases to extinction risks for an even larger fraction of species. However, there is *low agreement* on the numerical assessment because as more realistic details have been considered in models, it has been shown that extinction risks may be either under- or overestimated when using the simpler models (Section 4.3.2.5), among other reasons due to the existence of microrefugias or to delay in population decline leading to extinction debts (e.g., Dullinger et al., 2012). Additional risks include biome shifts of 400 km (Gonzalez et al., 2010), the disappearance of analogs of current climates in regions of exceptional biodiversity in the Himalayas, Mesoamerica, East and South Africa, the Philippines, and Indonesia (Beaumont et al., 2011), and loss of more than half of the climatically determined geographic ranges of 57 ± 6% of plants and 34 ± 7% of animals studied (Warren et al., 2013a). Widespread coral reef mortality is expected at 4°C due to the concomitant effects of warming and a projected decline of ocean pH of 0.43 since preindustrial times (*high confidence*; WGI AR5 Figure TS.20; Section 5.4.2.4; Boxes CC-CR, CC-OA). The corresponding CO_2 concentration in such a scenario is about 900 ppm (WGI AR5 Figure 12.36) whereas the onset of large-scale dissolution of coral reefs is projected if CO_2 concentrations reach 560 ppm (Sections 5.4.2.4, 26.4.3.2).

A number of studies project increases in water stress, flood, and drought in a number of regions with >4°C warming, and decreases in others (Li et al., 2009; Arnell, 2011; Fung et al., 2011; Dankers et al., 2013; Gerten et al., 2013; Gosling and Arnell, 2013). For example, projections of the proportion of global population exposed to water stress due to climate change range from 5 to 50% (Gosling and Arnell, 2013) by 2100. The proportion of cropland exposed to drought disaster (one or more months with Palmer Drought Severity Index (PDSI) drought indicator below –3) is projected to increase from 15% today to 44 ± 6% by 2100, based on a range of projections including some that reach or exceed 4°C global warming (Li et al., 2009). Concurrently irrigation water demand in currently cultivated areas in the North Hemisphere is projected to rise by 20% in the summer by 2100 under RCP8.5 due to climate change alone (Wada et al. 2013), although this could be partly buffered by decreasing evapotranspiration due to plant physiological responses to increased atmospheric CO_2 (Konzmann et al., 2013; Box CC-VW). One study (Portmann et al., 2013) projects that, by the 2080s under the RCP8.5 scenario, 27 to 50% (mean 38%) of the global population would experience at least a 10% decrease in groundwater resources, mostly in drier areas with high population density where water stress is more likely to occur. Concurrently, 20 to 45% of the population is projected to experience at least a 10% increase in groundwater resources under RCP8.5 in the 2080s. This is projected to occur mostly in wetter areas or those with low population density where it is less probable that water stress will be an issue. Another study projects that annual runoff will fall by up to 75% across the Danube and Mississippi river basins, and by up to 90% in the Amazon; while runoff is projected to either fall (by up to 75%) or to rise (by up to 30%) in the Murray Darling, and increase by up to 150% in the Ganges basin, and up to 80% in the Nile basin (Fung et al., 2011) with 4°C warming. Both studies are based on an ensemble of climate model projections. Under RCP8.5 in 2100, nine global hydrological models driven by five global circulation models project increases in flood frequency in over half of the land surface, and decreases in roughly a third of the land surface (Dankers et al., 2013). According to one study, even if the human population remained constant in Europe, without adaptation, 3.5°C to 4.8°C global warming by the 2080s would expose an additional 250,000 to 400,00 people to river flooding, doubling economic damages since 1961 to 1990, and expose an additional 850,000 to 5,550,000 to coastal flooding (Ciscar et al., 2011), compared to 36,000 in 1995.

Under 4°C warming most of the world land area will be experiencing 4°C to 7°C higher temperatures than in the recent past, which means that important tipping points for health impacts may be exceeded in many areas of the world during this century, including coping mechanisms for daily temperature/humidity, seasonally compromising normal human activities, including growing food or working outdoors (Chapter 11 ES). Exceedance of human physiological limits is projected in some areas for a global warming of 7°C, and in most areas for global warming of 11°C to 12°C (*low confidence*; Sherwood and Huber, 2010), a temperature increase that is possible by 2300 (WGI AR5 Figure 12.5).

The risk of large-scale singular events such as ice sheet disintegration, CH_4 release from clathrates, and regime shifts in ecosystems (including Amazon dieback), is higher with increased warming (and therefore higher above 4°C than below it) although there is *low confidence* in the temperature changes at which thresholds might exist for these processes (Section 19.6.3.6; WGI AR5 Sections 12.5.5, 13.4). There are also more gradual changes that become large with global temperature rise of 4°C or more, such as decline in the Atlantic Meridional Overturning Circulation (AMOC) and release of carbon from thawed permafrost (CTP). The AMOC is considered *very likely* to weaken for such warming, with best estimates of loss over the 21st century under RCP8.5 ranging from 12 to 54% (WGI AR5 Sections 12.4.7.2, 12.5.5.2). The best estimated range for CTP by 2100 is from 50 to 250 PgC for RCP8.5 (WGI AR5 Section 6.4.3.4) although there are large uncertainties. Larger decreases in AMOC and increases in CTP are thus implied for a global warming of above 4°C. Similarly, because a nearly ice-free Arctic Ocean in September before mid-century is likely under RCP8.5, by which time projected GMT rise amounts to 2.0 ± 0.4°C above the 1986–2005 baseline (*medium confidence*; WGI AR5 Section 12.4.6.1), the likelihood is even higher for global warming of above 4°C. Regions of the boreal forest could witness widespread forest dieback (*low confidence*), putting at risk the boreal carbon sink (Section 4.3.3.1.1; WGI AR5 Section 12.5.5). Forest susceptibility to fire is projected to increase substantially in many areas for the high emissions scenario (RCP 8.5; Section 4.3.3.1; Figure 4-6) and hence larger changes are implied for global warming above 4°C.

Based on the assessment in this section, we conclude that climate change impacts at 4°C and above would be of greater magnitude and more widespread than at lower levels of global temperature rise (*medium evidence*, *high agreement*; *high confidence*), extending to higher temperature levels previous findings that risks increase with increasing global average temperature (WGII AR4 SPM.2; National Research Council, 2011). Few studies yet consider the interactions between these effects, which could create significant additional risks (Warren et al., 2011; Sections 19.3-4).

19.5.2. Risks from Ocean Acidification

Ocean acidification is defined as "a reduction in pH of the ocean over an extended period, typically decades or longer, caused primarily by the uptake of carbon dioxide (CO_2) from the atmosphere" (WGI AR5 Section 3.3.2, Box 3.2; Box CC-OA; see also Glossary). Acidification is a physical and biogeochemical impact resulting from CO_2 emissions that poses risks to marine ecosystems and the societies that depend on them. Research on impacts on organisms, ecological responses, and consequences for ecosystem services is relatively new; the potential for associated risks to become key is magnified by the fact that acidification is a global phenomenon and, without a decrease in atmospheric CO_2 concentration, it is irreversible on century time scales.

It is *virtually certain* that ocean acidification is occurring now (WGI AR5 Section 3.9) and will continue to increase in magnitude as long as the atmospheric CO_2 concentration increases (National Research Council, 2010). Risks to society and ecosystems result from a chain of consequences

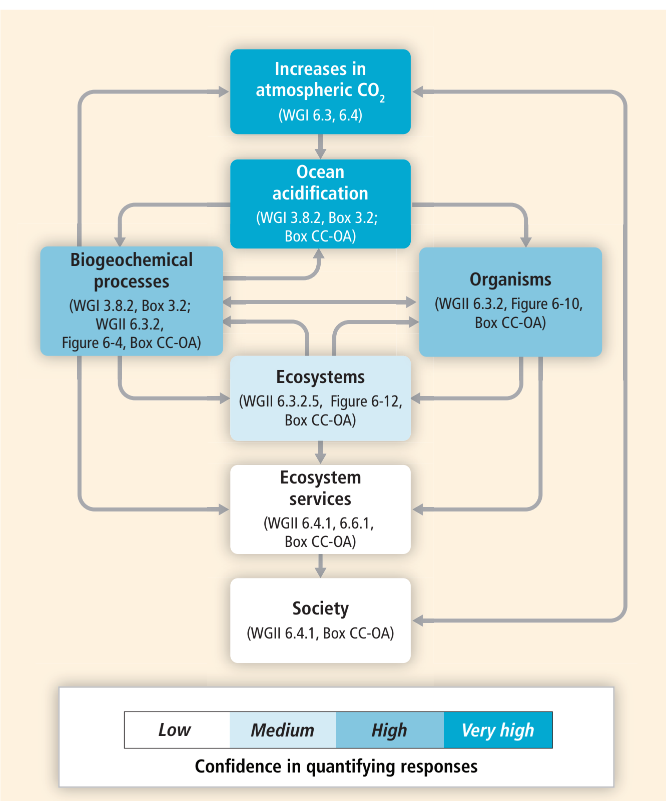

Figure 19-3 | The pathways by which ocean acidification affects marine processes, organisms, ecosystems, and society. The confidence in quantifying the impacts decreases along the pathway.

beginning with direct effects on biogeochemical processes and organisms and extending to indirect effects on ecosystems, ecosystem services, and society (Figure 19-3). The degree of confidence in assessing risks decreases along this chain owing to the complexity of interactions across these scales and the relatively small number of studies available for quantitative risk assessment.

Most studies have focused on the direct effects of ocean acidification on marine organisms and biogeochemical processes. The overall effects on organisms can be assessed with *medium confidence* (Section 6.3.2; Box CC-OA), but the effects vary widely across processes (e.g., photosynthesis, growth, calcification; Section 6.3.2) and across organisms and their life stages (Section 6.3.2; Box CC-OA).

Far fewer studies have assessed the impacts on ecosystems (Section 6.3.2.5) and ecosystem services (Section 6.4.1), and most of these studies have focused on the economic impacts on fisheries (Section 6.4.1.1). For example, changes in overall availability and nutritional value of desired mollusk species could affect economies (Narita et al., 2012) and food availability (Section 6.4.1.1). In Table 19-3, we assess the risks to ecosystem services through the impact of acidification on two key marine processes, calcification in warmwater corals and nitrogen fixation, using the criteria for key risks (Section 19.2.2.2).

Based on Table 19-3, the response of coral calcification to ocean acidification and the resulting consequences for coral reefs constitute a key risk to important ecosystem services (*high confidence*). The effect of ocean acidification on marine N_2-fixation could potentially become a key risk, given that it could have potentially large consequences for marine ecosystems, but currently there is *limited evidence* on the likelihood of this risk materializing.

19.5.3. Risks from Carbon Dioxide Health Effects

There is increasing evidence that the impacts of elevated atmospheric CO_2 on plant species will affect health via two distinct pathways: the increased production and allergenicity of pollen and allergenic compounds, and the nutritional quality of key food crops. The evidence for these impacts on plant species is increasingly *robust* and recent evidence in the public health literature points to a *medium* to *high confidence* in the potential for these risks to be sufficiently widespread in geographical scope and large in *magnitude* of their impact on human health to be considered key risks.

Climate change is expected to alter the spatial and temporal distribution of several key allergen-producing plant species (Shea et al., 2008), and increased atmospheric CO_2 concentration, independent of climate effects, has been shown to stimulate pollen production (Rasmussen, 2002; Clot, 2003; Galán et al., 2005; Garcia-Mozo et al., 2006; Ladeau and Clark, 2006; Damialis et al., 2007; Frei and Gassner, 2008). A series of studies (Ziska and Caulfield, 2000; Ziska et al., 2003; Ziska and Beggs, 2012) found an association of elevated CO_2 concentrations and temperature with faster growing and earlier flowering ragweed species (*Ambrosia artemisiifolia*) along with greater production of ragweed pollen (Wayne et al., 2002; Singer et al., 2005; Rogers et al., 2006), leading, in some areas, to a measurable increase in hospital visits for allergic rhinitis

Table 19-3 | An assessment of the risks to ecosystem services posed by the impacts of ocean acidification on warm-water coral calcification and nitrogen fixation, based on the four criteria for key risks (Section 19.2.2.2).

Criterion for key risk	Coral calcification	Nitrogen fixation
1. Magnitude of consequences for ecosystem services	Ecosystem services include supporting habitats, provisioning of fish, regulating shoreline erosion, and tourism. Potential magnitude of consequences is medium to high (Box CC-CR).	Ecosystem services include nitrogen cycling, which supports ecosystem structure and food chains (Hutchins et al., 2009). Potential magnitude of consequences has not been investigated.
2. Likelihood that risks will materialize and their timing	A reduction in coral calcification rate and an increase in reef dissolution rates are *very likely* (Section 6.1.2), so that reefs will progressively shift toward net dissolution (*medium confidence*; Section 5.4.2.4; Boxes CC-CR and CC-OA).	Both increases and decreases in nitrogen fixation have been observed in various N_2-fixing organisms (Section 6.3.2.2) but there is *limited* in situ *evidence* and *medium agreement* on how N_2-fixation rates will change in response to ocean acidification.
3. Irreversibility and persistence of ocean acidification impacts	Decreases in ocean pH will persist as long as atmospheric CO_2 levels remain elevated (WGI AR5 Section 3.8.2). Reductions in coral calcification will persist unless corals can physiologically adapt to maintain calcification rates. Reversibility of impacts on ecosystem services of coral reefs is unknown and depends on ecological factors such as hysteresis.	Decreases in ocean pH will persist as long as atmospheric CO_2 levels remain elevated (WGI AR5 Section 3.8.2). Reversibility and persistence of impacts on nitrogen fixation are unknown.
4. Limited ability to reduce the magnitude and frequency or nature of ocean acidification impacts	Reduction of ocean acidification will require global reductions in atmospheric CO_2. Feasibility of mitigating ocean acidification at the local scale is unknown.	Reduction of ocean acidification will require global reductions in atmospheric CO_2.

(Breton et al., 2006). Experimental studies have shown that poison ivy, another common allergenic species, responds to atmospheric CO_2 enrichment through increased photosynthesis, water use efficiency, growth, and biomass. This stimulation, exceeding that of most other woody species, also produces a more potent form of the primary allergenic compound, urushiol (Mohan et al., 2006).

While climate change and variability are expected to affect crop production (see Chapter 7), emerging evidence suggests an additional stressor on the food system: the impact of elevated levels of CO_2 on the nutritional quality of important foods. A prominent example of the effect of elevated atmospheric CO_2 is the decrease in the nitrogen concentration in vegetative plant parts as well as in seeds and grains and, related to this, the decrease in the protein concentrations (Cotrufo et al., 1998; Taub et al., 2008; Wieser et al., 2008). Experimental studies of increasing CO_2 to 550 ppm demonstrated effects on crude protein, starch, total and soluble beta-amylase, and single kernel hardiness, leading to a reduction in crude protein by 4 to 13% in wheat and 11 to 13% in barley (Erbs et al., 2010). Other CO_2 enrichment studies have shown changes in the composition of other macro- and micronutrients (calcium, potassium, magnesium, iron, and zinc) and in concentrations of other nutritionally important components such as vitamins and sugars (Idso and Idso, 2001). Declining nutritional quality of important global crops is a potential risk that would broadly affect rates of protein-energy and micronutrient malnutrition in vulnerable populations. While there is *medium confidence* that this risk has the potential to become key when judged by its *magnitude* and other criteria (Sections 19.2.2.1-2) there is currently insufficient information to assess under what ambient CO_2 concentrations this would occur.

19.5.4. Risks from Geoengineering (Solar Radiation Management)

Geoengineering refers to a set of proposed methods and technologies that aim to alter the climate system at a large scale to alleviate the impacts of climate change (see Glossary; IPCC, 2012b; WGI AR5 Sections 6.5, 7.7; WGIII AR5 Chapter 6). The main intended benefit of geoengineering would be the reduction of climate change that would otherwise occur, and the associated reduction in impacts (Shepherd et al., 2009). Here we focus on risks, consistent with the goal of this chapter. Although geoengineering is not a new idea (e.g., Rusin and Flit, 1960; Budyko and Miller, 1974; Enarson and Morrow, 1998; and a long history of geoengineering proposals as detailed by Fleming, 2010), it has received increasing attention in the recent scientific literature.

Geoengineering has come to refer to both carbon dioxide removal (CDR; discussed in detail in WGI AR5 Section 6.5, FAQ 7.3) and Solar Radiation Management (SRM; Izrael et al., 2009; Lenton and Vaughan, 2009; Shepherd et al., 2009; discussed in detail in WGI AR5 Section 7.7, FAQ 7.3). These distinct approaches to climate control raise very different scientific (e.g., Shepherd et al., 2009), ethical (Morrow et al., 2009; Preston, 2013), and governance (Lloyd and Oppenheimer, 2014) issues. Many approaches to CDR are considered to more closely resemble mitigation rather than other geoengineering methods (IPCC, 2012b). In addition, CDR is thought to produce fewer risks than SRM if the CO_2 can be stored safely (Shepherd et al., 2009) and unintended consequences for land use, the food system, and biodiversity can be avoided (Section 19.4.3). For these reasons, in addition to the more substantial recent literature on SRM's potential impacts, we address only SRM in this section. SRM is a potential key risk because it is associated with impacts to society and ecosystems that could be large in magnitude and widespread. Current knowledge on SRM is limited and our confidence in the conclusions in this section is *low*.

Studies of impacts on society and ecosystems have been based on two of the various SRM schemes that have been suggested: stratospheric aerosols and marine cloud brightening. These approaches in theory could produce large-scale cooling (Salter et al., 2008; Lenton and Vaughan, 2009), although it is not clear that it is even possible to produce a stratospheric sulfate aerosol layer sufficiently optically thick to be effective (Heckendorn et al., 2009; English et al., 2012). Observations of volcanic eruptions, frequently used as an analog for SRM (Robock et al., 2013), indicate that while stratospheric aerosols can reduce the global average surface air temperature, they can also produce regional drought (e.g., Oman et al., 2005, 2006; Trenberth and Dai, 2007), cause ozone depletion (Solomon, 1999), and reduce electricity generation from solar generators that use focused direct sunlight (Murphy, 2009). Climate modeling studies show that the risk of ozone depletion depends in detail on how much and when stratospheric aerosols would be released in the stratosphere (Tilmes et al., 2008) and find that global stratospheric SRM would produce uneven surface temperature responses and reduced precipitation (Schmidt et al., 2012; Kravitz et al., 2013), weaken the global hydrological cycle (Bala et al., 2008), and reduce summer monsoon rainfall relative to current climate in Asia and Africa (Robock et al., 2008). Hemispheric geoengineering would have even larger effects (Haywood et al., 2013).

The net effect on crop productivity would depend on the specific scenario and region (Pongratz et al., 2012). Use of SRM also poses a risk of rapid climate change if it fails or is halted suddenly (WGI AR5 Section 7.7; Jones et al., 2013), which would have large negative impacts on ecosystems (*high confidence*; Russell et al., 2012) and could offset the benefits of SRM (Goes et al., 2011). There is also a risk of "moral hazard"; if society thinks geoengineering will solve the global warming problem, there may be less attention given to mitigation (e.g., Lin, 2013). In addition, without global agreements on how and how much geoengineering to use, SRM presents a risk for international conflict (Brzoska et al., 2012). Because the direct costs of stratospheric SRM have been estimated to be in the tens of billions of U.S. dollars per year (Robock et al., 2009; McClellan et al., 2012), it could be undertaken by non-state actors or by small states acting on their own (Lloyd and Oppenheimer, 2014), potentially contributing to global or regional conflict (Robock, 2008a,b). Based on magnitude of consequences and exposure of societies with limited ability to cope, geoengineering poses a potential key risk.

19.6. Key Vulnerabilities, Key Risks, and Reasons for Concern

In this section, we present key vulnerabilities, key risks, and emergent risks that have been identified by many of the chapters of this report based on the material assessed by each in light of criteria discussed in Sections 19.2.2 and 19.2.3. We then discuss dynamic characteristics of exposure, vulnerability, and risk, features that are influenced by development pathways in the past, present, and future. Illustrative examples of climate-related hazards, key vulnerabilities, key risks, and emergent risks in Table 19-4 are representative, having been selected from a larger number provided by the chapters of this report. The table demonstrates how these four categories are related, as well as how they differ, and how they interact with non-climate stressors. The table also provides information on how key risks actually develop due to changing climatic hazards and vulnerabilities. This knowledge is an important prerequisite for effective adaptation and risk reduction strategies that must address climate-related hazards, non-climatic stressors, and various vulnerabilities that often interact in complex ways and change over time.

19.6.1. Key Vulnerabilities

Several of the risks discussed in this and other chapters and noted in Table 19-4 arise because vulnerable people must cope and adapt not only to changing climate conditions, but also to multiple, interacting stressors simultaneously (see Sections 19.3-4), which means that effective adaptation strategies would address these complexities and relationships.

19.6.1.1. Dynamics of Exposure and Vulnerability

This subsection deals with the meaning and the importance of dynamics of exposure and vulnerability, while Section 19.6.1.3 assesses recent literature regarding observed trends of vulnerability mostly at a global or regional scale. The literature provides increasing evidence that structures and processes that determine vulnerability are dynamic and spatially variable (IPCC, 2012a; Section 19.6.1.3). SREX states with *high confidence* that vulnerability and exposure of communities or social-ecological systems to climatic hazards related to extreme events are dynamic, thus varying across temporal and spatial scales due to influences of and changes in social, economic, demographic, cultural, environmental, and governance factors (IPCC, 2012c, SPM.B).

Examples of such dynamics in exposure and vulnerability encompass, for example, population dynamics, such as population growth or changes in poverty (Table 19-4; Birkmann et al., 2013b) and increasing exposure of people and settlements in low-lying coastal areas or flood plains in Asia (see Nicholls and Small, 2002; Fuchs et al., 2011; IPCC, 2012a; Peduzzi et al., 2012). Also, demographic changes, such as aging of societies, have a significant influence on people's vulnerability to heat stress (see Stafoggia et al., 2006; Gosling et al., 2009). Changes in poverty or socioeconomic status, ethnic compositions, as well as age structures had a significant influence on the outcome of past crises and in addition were modified and reinforced through disasters triggered by climate- and weather-related hazards. For the USA, for example, Cutter and Finch (2008) found that social vulnerability to natural hazards increased over time in some areas owing to changes in socioeconomic status, ethnic composition, age, and density of population. Changes in the strength of social networks (e.g., resulting in social isolation of elderly) and physical abilities to cope with such extreme events modify vulnerability (see, e.g., Khunwishit and Arlikatti, 2012).

In some cases human vulnerability might also change in different phases of crises and disasters. Hence, the factors that might determine vulnerability before a crisis or disaster (drought crises, flood disaster) might differ from those that determine vulnerability thereafter (post-disaster and recovery phases). Disaster response and reconstruction processes and policies can modify exposure and vulnerability, for example, of coastal communities (Birkmann and Fernando, 2008; Birkmann, 2011). A comprehensive assessment of vulnerability would account for these dynamics by evaluating long-distance impacts (e.g., resulting from migration or global influence of regional crop production failures following floods) and multiple stressors (e.g., recovery policies after disasters) that often influence dynamics and generate complex crises and even emergent risks. Furthermore, SREX also underscores that the increased intensity, frequency, and duration of some extreme events as climate continues to change might make adaptation based only on recent experience or the extrapolation of historical trends largely ineffective (Lavell et al., 2012, pp. 44–47); hence understanding the dynamics of vulnerability and its different facets is crucial.

19.6.1.2. Differential Vulnerability and Exposure

Wealth, education, ethnicity, religion, gender, age, class/caste, disability, and health status exemplify and contribute to the differential exposure and vulnerability of individuals or societies to climate and non-climate-related hazards (see IPCC, 2012a). Differential vulnerability is, for example, revealed by the fact that people and communities that are similarly exposed encounter different levels of harm, damage, and loss as well as success of recovery (see Birkmann, 2013). The uneven effects and uneven suffering of different population groups and particularly marginalized groups is well documented in various studies (Bohle et al., 1994; Kasperson and Kasperson, 2001; Birkmann, 2006a; Thomalla et al., 2006; Sietz et al., 2011, 2012). Factors that determine and influence these differential vulnerabilities to climate-related hazards include, for example, ethnicity (Fothergill et al., 1999; Elliott and Pais, 2006; Cutter and Finch, 2008), socioeconomic class, gender, and age (O'Keefe et al., 1976; Sen, 1981; Peacock, 1997; Jabry, 2003; Wisner, 2006; Bartlett, 2008; Ray-Bennett, 2009), as well as migration experience (Cutter and Finch, 2008) and homelessness (Wisner, 1998; IPCC, 2012a). Differential vulnerabilities of specific populations can often be discerned at a particular scale using quantitative or qualitative assessment methodologies (Cardona, 2006, 2008; Birkmann et al., 2013b). Various population groups are differentially exposed to and affected by hazards linked to climate change in terms of both gradual changes in mean properties and extreme events. For example, in urban areas, marginalized groups (particularly as a result of gender or wealth status or ethnicity) often settle along rivers or canals, where they are highly exposed to flood hazards or potential sea level rise (see Table 19-4; e.g., Neal and Phillips, 1990; Enarson and Morrow, 1998; Neumayer and Plümper, 2007; Sietz et al., 2012). Studies emphasize that vulnerability in terms of gender is not determined through biology, but in most cases by social structures, institutions, and rule systems; hence women and girls are often (not always) more vulnerable because they are marginalized from decision making or experience discrimination in development and reconstruction efforts (Fordham, 1998; Houghton, 2009; Sultana, 2010; IPCC, 2012a).

19.6.1.3. Trends in Exposure and Vulnerability

Vulnerability and exposure of societies and social-ecological systems to hazards linked to climate change are dynamic and depend on economic, social, demographic, cultural, institutional, and governance factors (see IPCC, 2012c, p. 7). The literature shows that there is a *high confidence* that rapid and unsustainable urban development, international financial pressures, increases in socioeconomic inequalities, failures in governance (e.g., corruption), and environmental degradation are key trends that modify vulnerability of societies, communities, and social-ecological systems (Maskrey, 1993a,b, 1994, 1998; Mansilla, 1996; Cannon, 2006; Birkmann, 2013; de Sherbinin, 2014) at different scales. Consequently, many of the factors that reveal and determine differential vulnerability change over time in terms of their spatial distribution. These dynamics unfold in different places differently and therefore local or regional specific strategies are needed that strengthen resilience (Garschagen and Kraas, 2011; Holdschlag and Ratter, 2013) and reduce exposure and vulnerability. For example, countries characterized by rapid urbanization coupled with low economic performance and high social development barriers face among the highest levels of climate change vulnerability. However, urbanization in some areas can yield conditions conducive to building up coping and adaptation capacities particularly when urban socioeconomic development and risk management is properly implemented (see Garschagen and Romero-Lankao, 2013). The following subsections outline observed trends in vulnerability according to different thematic dimensions (e.g., socioeconomic, environmental, institutional), within the constraint that relevant socioeconomic data are limited.

19.6.1.3.1. Trends in socioeconomic vulnerability

Multi-dimensional poverty is an important factor determining vulnerability of societies to climate change and extreme events (Section 13.1.4). For example, risk due to droughts, particularly in sub-Saharan Africa, is intimately linked to poverty and rural vulnerability (*high confidence*; see World Bank, 2010; Birkmann et al., 2011b; UNISDR, 2011, p. 62; Welle et al., 2012). In interpreting the following estimates, it should be borne in mind that diverse concepts of poverty lead to different estimates but that for some regions, e.g., sub-Saharan Africa, the trends are *robust*. Recent evaluation of conditions in 119 countries found that at the international level there had been a clear decrease in global poverty over the previous 6 years (Chandy and Gertz, 2011). The number of poor people globally fell, from more than 1.3 billion in 2005 to fewer than 900 million in 2010. This trend is expected to continue (e.g., Hughes et al., 2009; Chandy and Gertz 2011). However, regional trends vary, as do differences between emerging and least developed economies. As a result, there is a growing climate-related risk in some regions associated with chronic poverty. For example, in 2010, approximately 48.5% of the population of the highly drought exposed region sub-Saharan Africa still lives in poverty (poverty headcount ration at $1.25 per day; see World Bank, 2012) and this area already has been defined as a global risk hotspot (see Birkmann et al., 2011b; Welle et al., 2012). However, various national-level poverty statistics provide little information about the actual distribution of poverty, for example, between rural vs. urban areas. Income distribution trends show significant increases in inequality in some countries in Africa, and particularly in Asia, such as in China, India, Indonesia, and Bangladesh (World Bank, 2012). In Asia and Southeast Asia this trend overlaps with areas of compound climate risk (Section 19.3.2.4) in terms of people currently exposed to floods and tropical cyclones as well as sea level rise (Förster et al., 2011; IPCC, 2012a; Peduzzi et al., 2012). Assessing vulnerability (and risk) in these countries requires in-depth analysis of trends and distribution patterns of poverty, income disparities, and exposure of people to changing climatic hazards.

New socioeconomic vulnerabilities are emerging in some countries, for example, in developed countries, where the impoverishment of some population groups is observed. For example, research underscores that old age increases the risk of poverty in Greece, as the majority of people working as farmers or in the private sector receive small pensions that are below the poverty line (Karamessini, 2010, p. 279). These factors might interact with limited physical means of elderly to cope with climatic hazards, such as heat waves, and hence increase vulnerability.

Health status of individuals and population groups affects vulnerability to climate change by limiting capacities to cope and adapt to climate hazards (see Chapter 11). Although at a global scale the percentage of people undernourished is decreasing (FAO, 2012) and this trend is expected to continue (Hughes et al., 2009), the regional and national differences are significant: during 2010–2012, 870 million people remained chronically undernourished (FAO, 2012). Particularly in certain regions highly exposed to current and projected climate-related hazards, the number of people undernourished has increased. In sub-Saharan Africa, where exposure to drought is episodically high, the number of undernourished increased by 64 million or about 38% during 2010–2012 compared to 1990–1992 (Hughes et al., 2009; FAO, 2012, p. 10). Moreover, at many locations, climate change is expected to reduce the access to and the quality of natural resources that are important to sustain rural and urban livelihoods as well as the capacities of states to provide help to sustain livelihoods (Barnett and Adger, 2007; see also Section 19.3.2.1). These multi-risk contexts require new approaches for climate change adaptation.

While these trends mainly point to particularly large exposure and vulnerability in developing countries, studies regarding extreme heat vulnerability, for example, underscore that developed countries face increasing challenges to adaptation as well. Heat waves are projected to increase in duration, intensity, and extent (WGI AR5 Section 11.3.2). Advanced age represents one of the most significant risk factors for heat-related death (Bouchama and Knochel, 2002) because, in addition to limited thermoregulatory and physiologic heat-adaptation capacities, elderly have often reduced social contacts, and a higher prevalence of chronic illness and poor health (Section 11.3.3; Khosla and Guntupalli, 1999; Klinenberg, 2002; O'Neill, 2003). The trend toward an aging society, for example in Japan or Germany, therefore increases the vulnerability of these societies to extreme heat stress.

19.6.1.3.2. Trends in environmental vulnerability

Societies depend on ecosystem services for their survival; however, these ecosystem services and functions (see, e.g., Millenium Ecosystem Assessment, 2005a,b) are vulnerable to climate change (see Cardona et al., 2012, pp. 76–77; Table 19-4; Section 19.3.2.1). Various societies and communities that rely heavily on the quality of ecosystem services, such as rural populations dependent on rainfed agriculture where drying is projected (see also Table 19-4), will experience increased risk from climate change owing to its negative influence on ecosystem services (*high confidence*; see Sections 4.3.4, 6.4.1).

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Although no global overview is available, recent reports (UNDP, 2007; IPCC, 2012a) underscore that a number of current environmental trends threaten human well-being and thus increase human vulnerability (UNEP, 2007). Many communities that have suffered large losses due to extreme weather events—for example, coastal flooding—also experienced earlier degradation of ecosystems providing protective services. Recent global studies and local studies, such as for the U.S. East Coast, underscore that intact ecosystems, such as marshes, can have an important protective role against coastal hazards for example, by wave attenuation (Shepard et al., 2011; Beck et al., 2013). Hence, coastal degradation, such as destruction of coral reefs in Asia, is increasing the exposure of communities to such hazards (Welle et al., 2012). Moreover, the extinctions of species and the loss of biodiversity pose a threat of diminution of genetic pools that otherwise buffer the adaptive capacities of social-ecological systems dependent on these services in the medium and long run (e.g., in terms of medicine and agricultural production).

19.6.1.3.3. Trends in institutional vulnerability

Institutional vulnerability refers, among other issues, to the role of governance. Governance is increasingly recognized as a key factor that influences vulnerability and adaptive capacity of societies and communities exposed to extreme events and gradual climate change (Kahn, 2005; Nordås and Gleditsch, 2007; Welle et al., 2012). People in countries or places that are facing severe failure of governance, such as violent conflicts (e.g., Somalia, Afghanistan) are particularly vulnerable to extreme events and climate change, as they are already exposed to complex emergency situations and hence have limited capacities to cope or undertake effective risk management (see Ahrens and Rudolph, 2006; Menkhaus, 2010). Countries classified as failed states are often not able to guarantee their citizens basic standards of human security and consequently do not provide adequate or any support in crises or disaster situations for vulnerable people. The Failed State Index (Foreign Policy Group, 2012; Fund for Peace, 2012) as well as the Corruption Perception Index (Transparency International, 2012) are used to characterize institutional vulnerability and governance failure. Trends in the Failed State Index from 2006 to 2011 show that countries with severe problems in the functioning of the state cannot easily shift or change their situation (persistence of institutional vulnerability). Studies at the global level also confirm that countries classified as failed states and affected, for example, by violence are not able to effectively reduce poverty compared to countries without violence (see World Bank, 2011). Countries characterized in the literature as substantially failing in governance or in some particular aspects of governance during some period, such as Somalia and Ethiopia, Afghanistan, or Haiti have shown in the past severe difficulties in dealing with extreme events or supporting people that have to cope and adapt to severe droughts, storms, or floods (see, e.g., Lautze et al., 2004; Ahrens and Rudolph, 2006; Menkhaus, 2010, pp. 320-341; Heine and Thompson, 2011; Khazai et al., 2011, pp. 30-31). In addition, it is probable that climate change will undermine the capacity of some states to provide the services and support that help people to sustain their livelihoods in a changing climate (Barnett and Adger, 2007). Governance failure and violence as characteristics of institutional vulnerability have significant influence on socioeconomic and therefore climatic vulnerability. Furthermore, corruption has been identified as an important factor that hinders effective adaptation policies and crisis response strategies (Birkmann et al., 2011b; Welle et al., 2012). At the local level, various aspects of governance in developing and developed countries, particularly institutional capacities and self-organization, as well as political and cultural factors, are critical for social learning, innovations, and actions that can improve risk management and adaptation to climate related risks and for empowering highly vulnerable groups (IPCC, 2012a). Overall, unless governance improves in countries with severe governance failure, risk will increase and human security will be further undermined there as a result of climate change and increased human vulnerability (*high confidence*; Lautze et al., 2004; Ahrens and Rudolph, 2006; Barnett and Adger, 2007; Menkhaus, 2010).

19.6.1.4. Risk Perception

Risk perceptions influence the behavior of people in terms of risk preparedness and adaptation to climate change (Burton et al., 1993; van Sluis and van Aalst, 2006; IPCC, 2012a). Factors that shape risk perceptions and therewith also influence actual and potential responses (and thus exposure, vulnerability, and risk) include (1) interpretations of the threat, including the understanding and knowledge of the root cause of the problem; (2) exposure and personal experience with the events and respective negative consequences, particularly recently (i.e., availability); (3) priorities of individuals; (4) environmental values and value systems in general (see, e.g., O'Connor et al., 1999; Grothmann and Patt, 2005; Weber, 2006; Kuruppu and Liverman, 2011). Furthermore, the perceptions of risk and reactions to such risk and actual events are also shaped by motivational processes (Weber, 2010). In this context people will often ignore predictions of climate-related hazards if those predictions fail to elicit emotional reactions. In contrast, if the event or forecast of such an event elicits strong emotional feelings of fear, people may overreact and panic (see Slovic et al., 1982; Slovic, 1993, 2010; Weber, 2006). Public perceptions of risks are not determined solely by the "objective" information, but rather are the product of the interaction of such information with psychological, social, institutional, and cultural processes and norms that are partly subjective, as demonstrated in various crises in the context of extreme events (Kasperson et al., 1988; Funabashi and Kitazawa, 2012). Risk perceptions particularly influence and increase vulnerability in terms of false perceptions of security (Cardona et al., 2012, p. 70). Finally, it is important to acknowledge that everyday concerns and satisfaction of basic needs may prove more pressing than attention and effort toward actions to address longer-term risk factors, e.g., climate change (Maskrey, 1989, 2011; Wisner et al., 2004). Rather, peoples' worldviews and political ideologies guide attention toward events that threaten their preferred social order (Douglas and Wildavsky, 1982; Kahan, 2010).

19.6.2. Key Risks

19.6.2.1. Assessing Key Risks

Key risks arise from the interaction of climate-related hazards and key vulnerabilities of societies, communities, or systems exposed (see Figure 19-1). Various chapters in this report have assessed key risks from their particular perspectives. We asked each chapter writing team to provide Chapter 19 authors with the key risks of highest concern to their chapter based on the criteria for defining key risks and key vulnerabilities as outlined in Section 19.2.2. A complete presentation of the key risks provided is found in Box CC-KR (allowing for some condensation by authors of Chapter 19 to avoid repetition).

The key risks provided by the chapters represent the issues most pressing to each set of experts. The list is neither unique nor exhaustive: other authors might express other preferences; however, this compilation provides important insights about key risks and their determinants—hazard, exposure, and vulnerability.

Chapter 19 authors further consolidated these key risks in Table 19-4 in order to produce the following list which, in their judgment (*high confidence*), is representative of the range of key risks forwarded. Roman numerals preceding each key risk correspond with entries in Table 19-4. Each key risk is followed with a notation in brackets indicating the Reason(s) for Concern (RFCs; see Section 19.6.3) with which it is aligned. In addition, a representative set of lines of sight is provided from across the chapters. Examples of these risks are also displayed geographically in Figure 19-2:

i) *Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise*. These risks further increase in regions where the capacity to adapt long-lived coastal infrastructure (e.g. electricity, water and sanitation infrastructure) to local sea level rise beyond 1 m is limited. Urban populations with substandard housing and inadequate insurance, as well as marginalized rural populations with multidimensional poverty and limited alternative livelihoods are particularly vulnerable to these hazards. Inadequate local governmental attention to disaster risk reduction and adaptation can further increase the vulnerability of people and also the risk of adverse consequences (WGI AR5 Sections 3.7, 13.5; WGI AR5 Table 13.5; Sections 5.4.3, 8.1.4, 8.2.3-4, 13.1.4, 13.2.2, 24.4-5, 26.7-8, 29.3.1, 30.3.1; Boxes 25-1, 25-7). [RFC 1, 2, 3, 4, and 5]
ii) *Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions*. Particularly vulnerable are marginalized and poverty-stricken residents in low-income informal settlements as well as children, the elderly, and the disabled that have limited means to cope and adapt. Risks are increasing due to rapid and unsustainable urbanization especially in areas where risk governance capacities are constrained or limited attention is given to risk reduction and adaptation measures. Also, overwhelmed, aging, poorly maintained, and inadequate infrastructure (e.g., drainage infrastructure, electricity, water supply, etc.) can further increase the risk of severe harm and threats to human security in the case of inland flooding (WGI AR5 FAQ 12.2; Sections 3.2.7, 3.4.8, 8.2.3-4, 13.2.1, 25.10, 26.3, 26.7-8, 27.3.5; Box 25-8). [RFC 2 and 3]
iii) *Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services*. Interdependency of critical infrastructure increases the risk of systemic breakdowns of vital services, for example, the risk of failure in systems dependent on electric power (such as drainage systems reliant on electric pumps) during extreme events. Health and emergency services rely on critical infrastructure (e.g., telecommunication) that can be disrupted during such power failures. For example, Hurricane Katrina left 1220 electricity-dependent drinking water systems in Louisiana, Mississippi, and Alabama inoperable for several weeks (Copeland, 2005). Overly hazard-specific management planning and infrastructure design and/or low forecasting capabilities exacerbate such risks (WGI AR5 Section 11.3.2; Sections 8.1.4, 8.2.4, 10.2-3, 12.6, 23.9, 25.10, 26.7-8). [RFC 2, 3, and 4]
iv) *Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas*. Increasing frequency and intensity of extreme heat (including exposure to the urban heat island effect and air pollution) interacts with an inability of some local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups. In addition, the impact of heat stress on aging populations, such as during the heat wave disaster in 2003 in Europe, shows how changing climatic conditions interact with trends in population structure, health conditions, and social isolation (characteristics of vulnerability) to create key risks (WGI AR5 Section 11.3.2; Sections 8.2.3, 11.3,

11.4.1, 13.2, 23.5.1, 24.4.6, 25.8.1, 26.6, 26.8; Box CC-HS). [RFC 2 and 3]

v) *Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings*. This risk is a particular concern for farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers). Climatic hazards and the vulnerability of people (see above) may exacerbate malnutrition, giving rise to a larger burden of disease in these groups, especially among elderly and female-headed households having limited ability to cope. The reversal of progress in reducing malnutrition is a potential outcome (WGI AR5 Section 11.3.2; Sections 7.3-5, 11.3, 11.6.1, 13.2.1-2, 19.3.2, 19.4.1, 22.3.4, 24.4, 26.8, 27.3.4). [RFC 2, 3 and 4]

vi) *Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions*. Interaction of warming and drought with lack of alternative sources of income, and the presence of regional and national conditions that lead to a breakdown of food

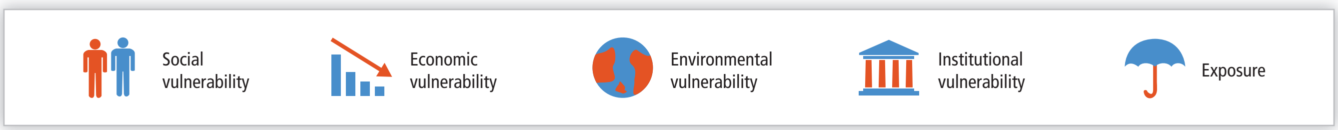
Table 19-4 | A selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapters 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, and 30). Key risks are determined by hazards interacting with vulnerability and exposure of human systems and of ecosystems or species. The table underscores the complexity of risks determined by various climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land tenure arrangements, unsustainable and rapid urbanization, other demographic changes, failure in governance and inadequate governmental attention to risk reduction, and tolerance limits of species and ecosystems that often provide important services to vulnerable communities, generate the context in which climatic change–related harm and loss can occur. The table illustrates that current global megatrends (e.g., urbanization and other demographic changes) in combination and in specific development contexts (e.g., in low-lying coastal zones) can generate new systemic risks in their interaction with climate hazards that exceed existing adaptation and risk management capacities, particularly in highly vulnerable regions, such as dense urban areas of low-lying deltas. Roman numerals correspond with key risks listed in Section 19.6.2.1. A representative set of lines of sight is provided from across WGI AR5 and WGII AR5. See Section 19.6.2.1 for a full description of the methods used to select these entries.

No.	Hazard	Key vulnerabilities	Key risks	Emergent risks
i	Sea level rise, coastal flooding including storm surges (WGI AR5 Sections 3.7 and 13.5; WGI AR5 Table 13.5; Sections 5.4.3, 8.1.4, 8.2.3, 8.2.4, 13.1.4, 13.2.2, 24.4, 24.5, 26.7, 26.8, 29.3.1, and 30.3.1; Boxes 25-1, 25-7)	High exposure of people, economic activity, and infrastructure in low-lying coastal zones, Small Island Developing States (SIDS), and other small islands Urban population unprotected due to substandard housing and inadequate insurance. Marginalized rural population with multidimensional poverty and limited alternative livelihoods Insufficient local governmental attention to disaster risk reduction	Death, injury, and disruption to livelihoods, food supplies, and drinking water Loss of common-pool resources, sense of place and identity, especially among indigenous populations in rural coastal zones	Interaction of rapid urbanization, sea level rise, increasing economic activity, disappearance of natural resources, and limits of insurance; burden of risk management shifted from the state to those at risk, leading to greater inequality
ii	Extreme precipitation and inland flooding (WGI AR5 FAQ 12.2; Sections 3.2.7, 3.4.8, 8.2.3, 8.2.4, 13.2.1, 25.10, 26.3, 26.7, 26.8, and 27.3.5; Box 25-8)	Large numbers of people exposed in urban areas to flood events, particularly in low-income informal settlements Overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure and limited ability to cope and adapt due to marginalization, high poverty, and culturally imposed gender roles Inadequate governmental attention to disaster risk reduction	Death, injury, and disruption of human security, especially among children, elderly, and disabled persons	Interaction of increasing frequency of intense precipitation, urbanization, and limits of insurance; burden of risk management shifted from the state to those at risk, leading to greater inequality, eroded assets due to infrastructure damage, abandonment of urban districts, and the creation of high-risk/high-poverty spatial traps
iii	Novel hazards yielding systemic risks (WGI AR5 Section 11.3.2; Sections 8.1.4, 8.2.4, 10.2, 10.3, 12.6, 23.9, 25.10, 26.7, and 26.8)	Populations and infrastructure exposed and lacking historical experience with these hazards Overly hazard-specific management planning and infrastructure design, and/or low forecasting capability	Failure of systems coupled to electric power system, e.g., drainage systems reliant on electric pumps or emergency services reliant on telecommunications. Collapse of health and emergency services in extreme events	Interactions due to dependence on coupled systems lead to magnification of impacts of extreme events. Reduced social cohesion due to loss of faith in management institutions undermines preparation and capacity for response.
iv	Increasing frequency and intensity of extreme heat, including urban heat island effect (WGI AR5 Section 11.3.2; Sections 8.2.3, 11.3, 11.4.1, 13.2, 23.5.1, 24.4.6, 25.8.1, 26.6, and 26.8; Box CC-HS)	Increasing urban population of the elderly, the very young, expectant mothers, and people with chronic health problems in settlements subject to higher temperatures Inability of local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups	Increased mortality and morbidity during periods of extreme heat	Interaction of changes in regional temperature extremes, local heat island, and air pollution, with demographic shifts Overloading of health and emergency services. Higher mortality, morbidity, and productivity loss among manual workers in hot climates
v	Warming, drought, and precipitation variability (WGI AR5 Section 11.3.2; Sections 7.3, 7.4, 7.5, 11.3, 11.6.1, 13.2.1, 13.2.2, 19.3.2, 19.4.1, 22.3.4, 24.4, 26.8, and 27.3.4)	Poorer populations in urban and rural settings are susceptible to resulting food insecurity; includes particularly farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers. Limited ability to cope among the elderly and female-headed households	Risk of harm and loss of life due to reversal of progress in reducing malnutrition	Interactions of climate changes, population growth, reduced productivity, biofuel crop cultivation, and food prices with persistent inequality and ongoing food insecurity for the poor increase malnutrition, giving rise to larger burden of disease. Exhaustion of social networks reduces coping capacity.

Continued next page →

Table 19-4 (continued)

No.	Hazard	Key vulnerabilities		Key risks	Emergent risks
vi	Drought (WGI AR5 Sections 12.4.1 and 12.4.5; Sections 3.2.7, 3.4.8, 3.5.1, 8.2.3, 8.2.4, 9.3.3, 9.3.5, 13.2.1, 19.3.2.2, and 24.4)	Urban populations with inadequate water services. Existing water shortages (and irregular supplies), and constraints on increasing supplies Lack of capacity and resilience in water management regimes including rural–urban linkages		Insufficient water supply for people and industry, yielding severe harm and economic impacts	Interaction of urbanization, infrastructure insufficiency, groundwater depletion
		Poorly endowed farmers in drylands or pastoralists with insufficient access to drinking and irrigation water Limited ability to compensate for losses in water-dependent farming and pastoral systems, and conflict over natural resources Lack of capacity and resilience in water management regimes, inappropriate land policy, and misperception and undermining of pastoral livelihoods		Loss of agricultural productivity and/or income of rural people. Destruction of livelihoods, particularly for those depending on water-intensive agriculture. Risk of food insecurity	Interactions across human vulnerabilities: deteriorating livelihoods, poverty traps, heightened food insecurity, decreased land productivity, rural outmigration, and increase in new urban poor in low- and middle-income countries. Potential tipping point in rain-fed farming system and/or pastoralism
vii	Rising ocean temperature, ocean acidification, and loss of Arctic sea ice (WGI AR5 Section 11.3.3; Sections 5.4.2, 6.3.1, 6.3.2, 7.4.2, 9.3.5, 22.3.2.3, 24.4, 25.6, 27.3.3, 28.2, 28.3, 29.3.1, 30.5, and 30.6; Boxes CC-OA and CC-CR)	High susceptibility of warm water coral reefs and respective ecosystem services for coastal communities; high susceptibility of polar systems, e.g., to invasive species Susceptibility of coastal and SIDS fishing communities depending on these ecosystem services; and of Arctic settlements and culture		Loss of coral cover, Arctic species, and associated ecosystems with reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms	Interactions of stressors such as acidification and warming on calcareous organisms enhancing risk
viii	Rising land temperatures, changes in precipitation patterns, and frequency and intensity of extreme heat (WGI AR5 Section 11.3.2.5; Sections 4.3.4, 19.3.2.1, 22.4.5.6, and 27.3.2.1; FAQs 4.5 and 4.7; Boxes 23-1 and CC-WE)	Susceptibility of societies to loss of provisioning, regulation, and cultural services from terrestrial ecosystems Susceptibility of human systems, agro-ecosystems, and natural ecosystems to (1) loss of regulation of pests and diseases, fire, landslide, erosion, flooding, avalanche, water quality, and local climate; (2) loss of provision of food, livestock, fiber, bioenergy; (3) loss of recreation, tourism, aesthetic and heritage values, and biodiversity		Reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms	Interaction of social-ecological systems with loss of ecosystem services upon which they depend



distribution and storage systems, increase risk. Especially vulnerable are those with limited ability to compensate for losses in water-dependent farming and pastoral systems, as well as those subject to conflict over natural resources. In addition, insufficient supply of water due to droughts and institutional vulnerabilities (e.g., lack of state capacities, conflicts) for both industry and urban populations lacking running water, yielding severe economic impacts and other harms (WGI AR5 Sections 12.4.1, 12.4.5; Sections 3.2.7, 3.4.8, 3.5.1, 8.2.3-4, 9.3.3, 9.3.5, 13.2.1, 19.3.2.2, 24.4). [RFC 2 and 3]

vii) *Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic*. These resources are especially at risk due to rising water temperature and the increase of stratification and ocean acidification. Loss of Arctic sea ice and degradation of coral reefs, as well as other natural barriers, presents a high risk to ecosystem services where many people are exposed to coastal hazards and also depend on coastal resources for livelihoods, such as Alaska, the Philippines, and Indonesia (WGI AR5 Section 11.3.3; Sections 5.4.2, 6.3.1-2, 7.4.2, 9.3.5, 22.3.2.3, 24.4, 25.6, 27.3.3, 28.2-3, 29.3.1, 30.5-6; Boxes CC-OA, CC-CR). [RFC 1, 2, and 4]

viii) *Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods*. Biodiversity and terrestrial ecosystem services are important for rural and urban communities globally. These services are at risk due to rising temperatures, changes in precipitation patterns, and extreme weather events. Risks are high for communities whose livelihoods depend on provisioning services. Human and natural systems are susceptible to loss of provisioning services such as food and fiber, regulating services such as water quality, fire, and erosion, and cultural services such as aesthetic values and tourism (WGI AR5 Section 11.3.2.5; Sections 4.3.4, 19.3.2.1, 22.4.5.6, 27.3.2.1; Boxes 23-1, CC-WE; FAQs 4.5, 4.7). [RFC 1, 3 and 4]

An important common characteristic of all key risks associated with anthropogenic climate change is that they are determined by hazards due to changing climatic conditions on the one hand and the vulnerability of exposed societies, communities, and social-ecological systems, for example, in terms of livelihoods, infrastructure, ecosystem services and management/governance systems on the other (see Table 19-4). The compilation of key risks underscores that effective adaptation and risk reduction measures would address all three components of risk (*high confidence*).

19.6.2.2. The Role of Adaptation and Alternative Development Pathways

As discussed in Section 19.2.4, the identification of key risks depends in part on the underlying socioeconomic conditions assumed to occur in the future, which can differ widely across alternative development pathways. This section assesses literature that compares impacts across development pathways, compares the contributions of anthropogenic climate change and socioeconomic development (through changes in vulnerability and exposure) to climate-related impacts, and examines the potential for adaptation to reduce those impacts. Based on this assessment, risks vary substantially across plausible alternative development pathways and the relative importance of development and climate change varies by sector, region, and time period, but in general both are important to understanding possible outcomes (*high confidence*). In some cases, there is substantial potential for adaptation to reduce risks, with development pathways playing a critical role in determining challenges to adaptation, including through their effects on ecosystems and ecosystem services (Rothman et al., 2014).

Direct comparison of impacts across alternative development pathways shows, for example, that socioeconomic conditions are an important determinant of the impacts of climate change on food security, water stress, and the consequences of extreme events and sea level rise. The additional effect of climate change and CO_2 fertilization on the number of people at risk from hunger by 2080 generally spans a range of ± 10 to 30 million across the four marker SRES scenarios, each of which assumes different socioeconomic futures. However, in a scenario (A2) with high population growth and slow economic growth, this effect becomes as high as 120 to 170 million in some analyses (Schmidhuber and Tubiello, 2007). Similarly, the number of people exposed to water scarcity in a global study is sensitive to population growth assumptions (Gosling and Arnell, 2013), as are projected water resources in the Middle East under an A1B climate change scenario (Chenoweth et al., 2011). Assessments of the risks from river flooding depend on alternative future population and land use assumptions (Bouwer et al., 2010; te Linde et al., 2011), and sea level rise impacts depend on development pathways through their effect on the exposure of both the population and economic assets to coastal impacts, as well as on the capacity to invest in protection (Anthoff et al., 2010).

The view that development pathways are an important determinant of risk related to climate change impacts is further supported by two other types of studies: those that examine the vulnerability of subgroups of the current population, and those that compare the relative importance of climate and socioeconomic changes to future impacts. The first type finds that variation in current socioeconomic conditions explains some of the variation in risks associated with climate and climate change, supporting the idea that alternative development pathways, which describe different patterns of change in these conditions over time, should influence the future risks of climate change. For example, socioeconomic conditions have been found to be a key determinant of risks to low-income households due to climate change effects on agriculture (Ahmed et al., 2009; Hertel et al., 2010), to sub-populations due to exposure to heterogeneous regional climate change (Diffenbaugh et al., 2007), and to low-income coastal populations due to storm surges (Dasgupta et al., 2009). Assessments of environmentally induced migration have concluded that migration responses are mediated by a number of social and governance characteristics that can vary widely across societies (Warner, 2010; see Sections 12.4, 19.4.2.1).

The second type of study finds that, within a given projection of future climate change and change in socioeconomic conditions, typically both are important to determining risks. In fact, the effect of the physical impacts of climate change on globally aggregated changes in food consumption or risk of hunger have been found to be small relative to changes in these metrics driven by socioeconomic development alone (Schmidhuber and Tubiello, 2007; Nelson et al., 2010; Wiltshire et al., 2013). Similarly, future population growth is found to be an equally (Murray et al., 2012) or more (Fung et al., 2011; Schewe et al., 2013) important determinant of globally aggregated water stress as the level of climate change, and population growth, economic growth, and urbanization are expected to largely drive potential future damages to coastal cities due to flooding (*high confidence*; Section 5.4.3.1; Hallegatte et al., 2013) and to be important determinants of damages from tropical cyclones (Bouwer et al., 2007; Pielke Jr., 2007; Mendelsohn et al., 2012). At the regional level, socioeconomic development has also been found to be equally or more important than climate change to impacts in Europe due to sea level rise, through coastal development (Hinkel et al., 2010); heat stress, especially when acclimatization (Watkiss and Hunt, 2012) or aging (Lung et al., 2013) is taken into account; and flood risks, through exposure due to land use and distributions of buildings and infrastructure (Feyen et al., 2009; Bouwer et al., 2010). Climate change was the dominant driver of flood risks in Europe when future changes in the value of buildings and infrastructure at risk were excluded from the analysis (te Linde et al., 2011; Lung et al., 2013) or when biophysical impacts such as stream discharge, rather than its consequences, were assessed (Ward et al., 2011).

Land use is another socioeconomic factor that can affect risks in addition to climate change, but until recently few studies have addressed the combined impacts of climate change and land use on ecosystems (Warren et al., 2011). Studies including multiple drivers of extinction find that although land use change remains the dominant driver out to 2100, climate change is the next most important driver (Sala et al., 2000; Millenium Ecosystem Assessment, 2005b). A study of land bird extinction risk found some sensitivity to four alternative land use scenarios, but by 2100 risk was dominated by the climate change scenario (Şekercioğlu, 2008). A study of European land use found that while land use outcomes were more sensitive to the assumed socioeconomic scenario, consequences for species depended more on the climate scenario (Berry et al., 2006).

Explicit assessments of the potential for adaptation to reduce risks have indicated that there is substantial scope for reducing impacts of several types, but the capacity to undertake this adaptation is dependent on underlying development pathways. Assessments of the impacts of sea level rise, for example, show that if development pathways allow for substantial investment of resources in adaptation through coastal protection, as opposed to accommodation or abandonment strategies, reducing impacts by investing in coastal protection can be an economically rational response for large areas of coastline globally (Nicholls et al., 2008a,b; Anthoff et al., 2010; Nicholls and Cazenave, 2010; Hallegatte et al., 2013) and in Europe (Bosello et al., 2012b). For the specific case of sea level rise impacts in Europe, adaptation in the form of increasing dike heights and nourishing beaches, at a cost reaching about €3 billion per year by 2100, was found to reduce the number of people affected by coastal flooding in 2100 from hundreds of thousands to a few thousand per year depending on the socioeconomic and sea level rise scenario (A2 vs. B1), and total economic damages from about €17 billion to about €2 billion per year (Hinkel et al., 2010). In contrast, in some areas with higher current and anticipated future vulnerability such as low-lying island states and parts of Africa and Asia, impacts are expected to be greater and adaptation more difficult (Nicholls et al., 2011).

Similarly, the risk to food security in many regions could be reduced if development pathways increase the capacity for policy and institutional reform, although most impact studies have focused on agricultural production and accounted for adaptation to a limited and varying degree (Lobell et al., 2008; Nelson et al., 2009; Ziervogel and Ericksen, 2010). A study of response options in sub-Saharan Africa identified some scope for adapting to climate change associated with a global warming of 2°C above preindustrial levels (Thornton et al., 2011), given substantial investment in institutions, infrastructure, and technology, but was pessimistic about the prospects of adapting to a world with 4°C of warming (Thornton et al., 2011; see also Section 19.7.1). Improved water use efficiency and extension services have been identified as the highest priority agricultural adaptation options available in Europe (Iglesias et al., 2012), and a potentially large role for expanded desalination has been identified for the Middle East (Chenoweth et al., 2011).

19.6.3. Updating Reasons for Concern

The RFCs are the relationship between global mean temperature increase and five categories of impacts that were introduced in the IPCC TAR (Smith et al., 2001) in order to facilitate interpretation of Article 2

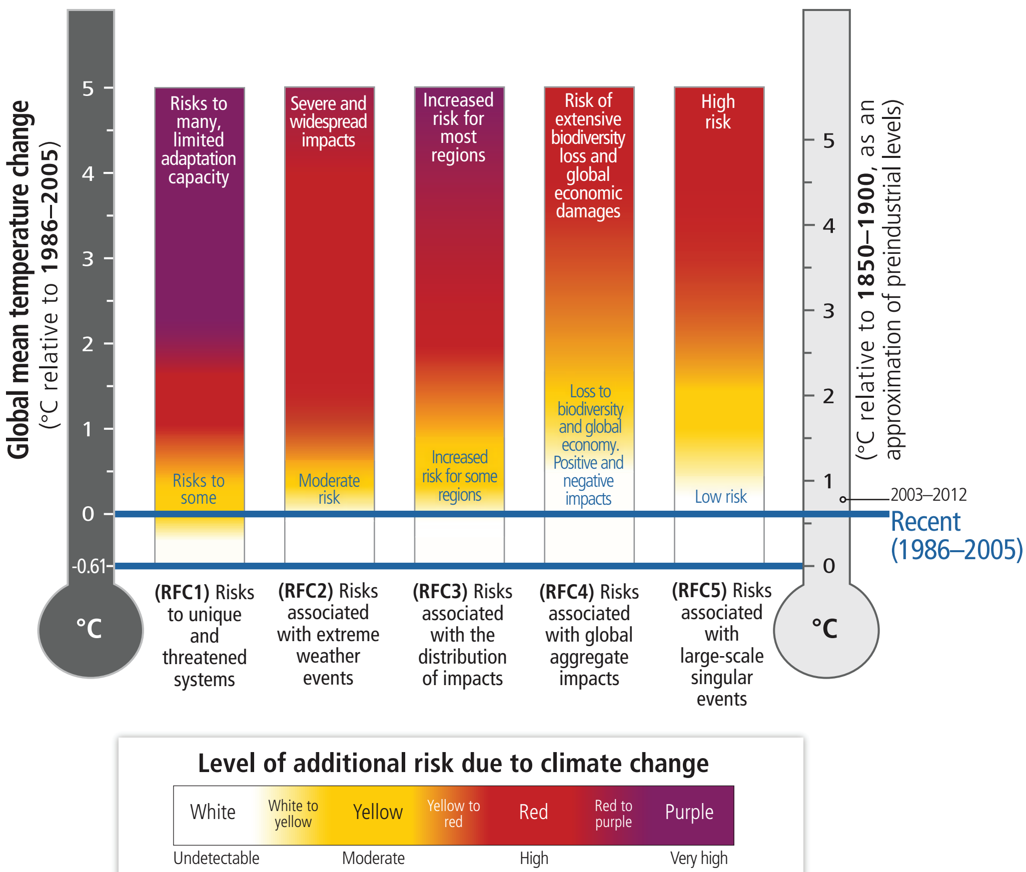


Figure 19-4 | The dependence of risk associated with the Reasons for Concern (RFCs) on the level of climate change, updated from the Third Assessment Report and Smith et al. (2009). The color shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual "reason." Undetectable risk (white) indicates no associated impacts are detectable and attributable to climate change. Moderate risk (yellow) indicates that associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks. High risk (red) indicates severe and widespread impacts, also accounting for the other specific criteria for key risks. Purple, introduced in this assessment, shows that very high risk is indicated by all specific criteria for key risks. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMT. In general, assessment of RFCs takes autonomous adaptation into account, as was done previously (Smith et al., 2001, 2009; Schneider et al., 2007). In addition, this assessment took into account limits to adaptation in the case of RFC1, RFC3, and RFC5, independent of the development pathway. The rate and timing of climate change and physical impacts, not illustrated explicitly in this diagram, were taken into account in assessing RFC1 and RFC5. Comments superimposed on RFCs provide additional details that were factored into the assessment. The levels of risk illustrated reflect the judgments of Chapter 19 authors.

(Section 1.2.2; Box 19-2). In AR4, new literature related to the five RFCs was assessed, leading in most cases to confirmation or strengthening of the judgments about their relevance to defining dangerous anthropogenic interference based on evidence that some impacts were already apparent, higher likelihoods of some climate-related hazards, and improved identification of currently vulnerable populations (Schneider et al., 2007; Smith et al., 2009).

RFCs are related to the framework of key risks, climate-related hazards, and vulnerabilities used in this chapter because each RFC is understood to represent a broad category of key risks to society or ecosystems associated with a specific type of hazard (extreme weather events, large-scale singular events), system at risk (unique and threatened systems), or characteristic of risk to social-ecological systems (global aggregate impacts on those systems, distribution of impacts to those systems). For example, the RFC for extreme weather events implies a concern for risks to society and ecosystems posed by extreme events,

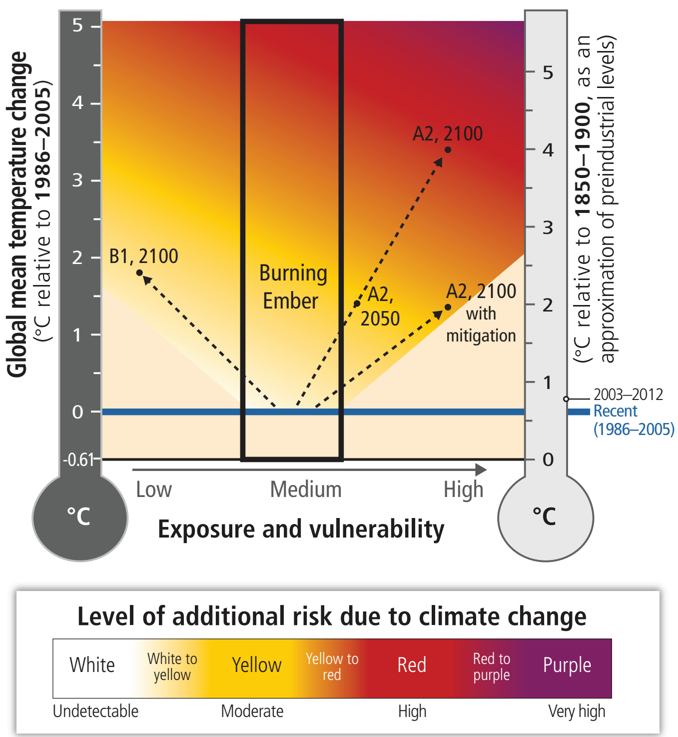


Figure 19-5 | Illustration of the dependence of risk associated with a Reason for Concern (RFC) on the level of climate change and exposure and vulnerability (E&V) of society. This figure is schematic; the degree of risk associated with particular levels of climate change or E&V has neither been based on a literature assessment nor associated with a particular RFC (the "burning ember" in the figure refers generically to any of the embers in Figure 19-4). The E&V axis is relative rather than absolute. "Medium" E&V indicates a future development path in which E&V changes over time are driven by moderate trends in socioeconomic conditions. "Low" and "High" E&V indicate futures that are substantially more optimistic or pessimistic, respectively, regarding exposure and vulnerability. Judgments made in other burning ember diagrams of the RFCs (Smith et al., 2001, 2009) including Figure 19-4, which do not explicitly take changes in E&V into account, are consistent with Medium future E&V. Arrows and dots illustrate the use of Special Report on Emission Scenarios (SRES)-based literature to locate particular impact or risk assessments on the figure according to the evolution of climate and socioeconomic conditions over time. This figure does not explicitly address issues related to the rates of climate change or when impacts might be realized.

rather than a concern for extreme events per se. Accordingly, in this chapter we have reworded the definition of RFCs to emphasize risk.

In this section we assess new literature related to each of the RFCs, concluding that, compared to judgments presented in AR4 and in Smith et al. (2009), levels of risk associated with extreme weather events and distribution of impacts can be assessed with higher confidence and are higher for large temperature rise than previously assessed; risks associated with global aggregate impacts are similar to AR4 and Smith et al (2009) and confidence in the assessment unchanged; and risks to unique and threatened systems and those associated with large-scale singular events are higher above 2°C (compared to a 1986–2005 baseline) than assessed previously. These judgments are illustrated in Figure 19-4, an updated version of the "burning embers" diagram that describes how the additional risk due to climate change for each RFC changes with increasing GMT. We retain the color scheme employed in previous versions of this figure (Smith et al., 2001, 2009) with some refinement. White, yellow, and red indicate undetectable, moderate, and high additional risk, respectively. Risk is low in the transition between white and yellow, and substantial in the transition between yellow and red. We add a new color (purple) indicating very high risk as elaborated below.

The following subsections assess risks for each RFC and locate transitions between colors using the criteria for key risks as a guide (Section 19.2.2.2). The transition from white to yellow is partly defined by the GMT at which there is at least *medium confidence* that impacts associated with a given risk are both detectable and attributable to climate change, while also accounting for the magnitude of the risk. We draw on Section 18.6.4 to inform the placement of this transition relative to recent GMT. The transition from yellow to red is defined by increasing magnitude (including pervasiveness) or likelihood of impacts, with high risk (red color) defined as risk of severe and widespread impacts that is judged to be high on one or more criteria for assessing key risks (Section 19.2.2.2). Purple, introduced in this assessment, shows that very high risk is indicated by all specific criteria for key risks, including limited ability to adapt. As was true in the TAR and Smith et al. (2009), transitions are fuzzy owing to uncertainties in a variety of factors determining the relation between GMT and risk, including the rate of climate change, the time at which the temperature is reached, and the extent and agreement of the evidence base in the literature.

We also clarify the concept of RFCs: because risks depend not only on physical impacts of climate change but also on exposure and vulnerability of societies and ecosystems to those impacts, RFCs as a reflection of those risks depend on both factors as well (see also Section 19.1).

19.6.3.1. Variations in RFCs across Socioeconomic Pathways

The determination of key risks as reflected in the RFCs has not previously been distinguished across alternative development pathways. In the TAR and AR4, RFCs took only autonomous adaptation into account (Smith et al., 2001; Schneider et al., 2007; WGII AR4 Chapter 19). However, the RFCs represent risks that are determined by both climate-related hazards and the vulnerability and exposure of social and ecological systems to climate change stressors. Figure 19-5 illustrates this dependence on vulnerability and exposure in a modified version of the burning embers diagram. Current literature is not sufficient to support confident assessment of specific RFCs using this approach.

As literature accumulates, it could inform new versions of this figure applied to specific RFCs. For example, studies that employ particular scenarios of socioeconomic conditions could be categorized according to the levels of vulnerability represented by those scenarios (van Vuuren et al., 2012) to locate results along the horizontal axes, while climate conditions assumed in those studies would locate results along the vertical axis. As with previous versions of the burning embers, however, this new figure does not explicitly address issues related to rates of climate change or to when impacts might be realized. The updates of RFCs in 19.6.3.2 to 19.6.3.6 that follow (and are illustrated in Figure 19-4) do not account for differences in vulnerability across development paths; rather, they are based on the same assessment framework as used in AR4 and Smith et al. (2009), but with additional elaboration.

19.6.3.2. Unique and Threatened Systems

Unique and threatened systems include a wide range of physical, biological, and human systems that are restricted to relatively narrow geographical ranges and are threatened by future changes in climate (Smith et al., 2001). Where consequences are *irreversible* and *importance* to society and other systems is high, the potential for loss of or damage to such systems constitutes a key risk. AR4 stated with *high confidence* that a warming of up to 2°C above preindustrial levels would result in significant impacts on many unique and vulnerable systems and would increase the endangered status of many threatened species, with increasing adverse impacts (and increasing confidence in this conclusion) at higher temperatures (Schneider et al., 2007). Since AR4, there is a growing body of literature suggesting that the number of threatened systems and species is greater than previously thought.

Chapters 4, 22, 23, 24, 25, 26, and 27 highlight areas where unique and threatened systems are particularly vulnerable to climate change. Evidence for severe and widespread impacts to humans and social systems, ecosystems, and species in polar regions as warming progresses has continued to accrue (Sections 4.3.3.4, 28.2). Projections of Arctic sea ice melt rates have increased since AR4 (WGI AR5 Section 12.4.6), increasing risks to the Inuit and the sea ice-dependent ecosystems upon which they subsist. CMIP5 model runs for September with all RCPs show substantial additional losses of Arctic Ocean ice for a global warming of 1°C relative to 1986–2005 and a nearly ice-free Arctic Ocean for global warming greater than 2°C (WGI AR5 Figure 12.30). Furthermore, a nearly ice-free Arctic Ocean in September before mid-century is *likely* under RCP8.5 (*medium confidence*; WGI AR5 Section 12.4.6).

Coral reef ecosystems are still considered amongst the most vulnerable of unique marine systems (Sections 5.4.2.4, 19.3.2.4), with corals' evolutionary responses being outpaced by climate change (Hoegh-Guldberg, 2012) resulting in projections of extensive reef decline throughout the 21st century. Globally, large-scale reef dissolution may occur if CO_2 concentrations reach 560 ppm (Section 5.4.2.4) due to the combined effects of warming and ocean acidification. Even if global temperature rise in the 2090s is constrained to 1.2 to 2.0°C above preindustrial levels (WGI AR5 Table 12.3, RCP2.6), and assuming rapid adaptation rates in corals, 9 to 60% of reefs are projected to be subject to long-term degradation, while 30 to 88% of reefs are projected to eventually degrade if global temperature rises in the 2090s by 1.9 to 2.9°C above preindustrial levels (RCP4.5; Box CC-CR; temperatures from WGI AR5 Table 12.3). Loss of corals and mangrove ecosystems would endanger the livelihoods of unique human communities and cause economic damage (Section 4.3.3 for global discussion; Sections 22.3.2.3, 24.4.3, 25.6 for Africa, Asia, and Australia; Section 26.4 for North America; Section 27.3.3.1 for South America).

There is a large and increasing amount of evidence for escalating risks of species range loss, extirpation, and extinction based on studies for global temperatures exceeding 2°C above preindustrial levels (1.4°C above 1986–2005; Warren et al., 2011; Şekercioğlu et al., 2012, Foden et al., 2013; Warren et al., 2013a). An assessment of 16,857 species (Foden et al., 2013) found that with approximately 2°C of warming above preindustrial (A1B, 2050s), 24 to 50% of the birds, 22 to 44% of the amphibians, and 15 to 32% of the corals were highly vulnerable to climate change defined as having high sensitivity, high exposure, and low adaptive capacity.

An increasing number of threatened systems has been identified, in the form of projected species range losses and extinction risks, although without yet tying risks to specific levels of warming. Evidence of climate risks to unique mountain ecosystems and their numerous endemic alpine species has continued to accrue in Europe, Asia, Australia, and South America (Sections 23.6.4, 24.4.2.3, 25.6.1, 27.3.2.1). Siberian, tropical, and desert ecosystems in Asia (Section 24.4.2.3), Africa (Warren et al., 2013a), and Mediterranean areas in Europe (Klausmeyer and Shaw, 2009; Maiorano et al., 2011), the Queensland rainforest, Kakadu National Park, and the southwestern region of Australia (Section 25.6.1), Amazonian ecosystems in South America (Foden et al., 2013; Warren et al., 2013a), and freshwater ecosystems in Africa (specifically Ethiopia, Malawi, Mozambique, Zambia, and Zimbabwe) (Section 22.3.2.2) are particularly at risk, as are the Fynbos and succulent Karoo areas of South Africa (Midgley and Thuiller, 2011; Kuhlmann et al., 2012; Huntley and Barnard, 2012) and dune systems in temperate climates (Section 23.6.5). Recent research has identified risks to highly biodiverse tropical wet and dry forests (Sections 4.3.3, 24.4.2.3; Kearney et al., 2009, Wright et al., 2009; Toms et al., 2012) and tropical island endemics (Fordham and Brook, 2010). Globally amphibians were found to be the most vulnerable of vertebrate taxa (Stuart et al., 2004; Brito, 2008; Rohr and Raffel, 2010; Liu et al., 2013; Warren et al., 2013a).

Owing to higher projections of sea level rise than in AR4 (WGI AR5 Sections 13.5-7), risk of partial inundation of small island states has increased.

"Since AR4, almost all glaciers worldwide have continued to shrink as revealed by the time series of measured changes in glacier length, area, volume and mass (*very high confidence*)" (WGI AR5 Chapter 4 ES). There is substantial new evidence that, across most of Asia, glaciers have been shrinking, except in some areas in the Karakorum and Pamir (Section 18.5.3). In the Andes, glacier loss threatens to reduce the water and electricity supplies of large cities and hydropower projects, as well as the agricultural and tourism sectors (Sections 27.3.1.1-2, 27.6.1; Table 27-3). Model simulations show a large projected loss of glacier ice volume in central Asia by end of the century: in particular, estimates for

RCP8.5 and RCP4.5 suggest the potential for loss of most of the 2006 ice volume (Section 24.9.2). Loss of glacial cover has been projected to significantly reduce water supplies in meltwater-dependent arid regions (Kaser et al., 2010), potentially threatening the food security of 60 million people in the Brahmaputra and Indus basins by the 2050s (Immerzeel et al., 2010). However, recent work has suggested the glacier melt rates in two Himalayan watersheds, Baltoro and Langtang, were previously overestimated and, since precipitation is projected to concurrently increase, runoff may actually rise until 2050 in these particular watersheds (Immerzeel et al., 2013). Large uncertainties in projections of Himalayan ice cover and runoff dynamics remain (Bolch et al., 2012).

In Figure 19-4, we locate the transition to moderate risk (white to yellow) below recent global temperatures because there is at least *medium confidence* in attribution of a major role for climate change for impacts on at least one each of ecosystems, physical systems, and human systems (Section 18.6.4). A transition to purple is located around 2°C above 1986–2005 levels to reflect the very high risk to species and ecosystems projected to occur beyond that level as well as limited ability to adapt to impacts on coral reef systems and on Arctic sea ice-dependent systems (Chapters 4, 5, 6, 28) if that level of warming were exceeded (*high confidence*). A transition to red is located around 1°C above 1986–2005 levels, midway between current temperature and the transition to purple, indicating the increasing risk to unique and threatened systems, including Arctic sea ice and coral reefs, as well as threatened species as temperature increases over this range.

19.6.3.3. Extreme Weather Events

Extreme weather events (e.g., heat waves, intense precipitation, drought, tropical cyclones) trigger impacts that can pose key risks to societies that are exposed and vulnerable (Lavell et al., 2012). With regard to the physical hazard aspect of risk, AR5 assesses a higher likelihood of attribution of heat waves and extreme hot days and nights to human activity than AR4. WGI AR5 states, "We assess that it is *very likely* that human influence has contributed to the observed changes in the frequency and intensity of daily temperature extremes on the global scale since the mid-20th century" (WGI AR5 Section 10.6.1.1) and "it is *likely* that human influence has substantially increased the probability of occurrence of heat waves in some locations" (WGI AR5 Section 10.6.2). WGI finds *medium confidence* in attribution of intensification of heavy precipitation over land areas with sufficient data (WGI AR5 Section 10.6.1.2), and "*low confidence* in detection and attribution of changes in drought over global land areas" (WGI AR5 Section 10.6.1.3) and global changes in tropical cyclone activity (WGI AR5 Section 10.6.1.5) to human influence. There is *high confidence* in attribution of impacts of weather extremes (as opposed to the physical hazards alone) on coral reef systems (Sections 18.6.4, 19.6.3.2; Table 18-10), with evidence for impact attribution limited and highly localized otherwise.

The likelihood of projected 21st century changes in extremes has not changed markedly since AR4 (WGI AR5 Chapters 10, 12), but for the first time near-term changes (for the period 2016–2035 relative to 1986–2005) are assessed (WGI AR5 Chapter 1), a period during which the increase in the model and scenario averaged GMT is projected to remain below 1°C relative to 1986–2005 (WGI AR5 Figure 11.8; WGI AR5 Section 11.3.6.3). Among the conclusions are, "In most land regions the frequency of warm days and warm nights will *likely* increase in the next decades, while that of cold days and cold nights will decrease" (WGI AR5 Chapter 11 ES). Specifically, about 15% of currently observed maximum daily temperatures exceed the historical 90th percentile values (rather than the historical 10%) and, by about 2035, 25 to 30% of daily maximums are projected to exceed the historical 90th percentile value (WGI AR5 Figure 11.17). WGI also notes that "Models project near-term increases in the duration, intensity and spatial extent of heat waves and warm spells" (WGI AR5 Chapter 11 ES; WGI AR5 Table SPM.1). With regard to extreme precipitation events, WGI finds "The frequency and intensity of heavy precipitation events over land will *likely* increase on average in the near term. However, this trend will not be apparent in all regions because of natural variability and possible influences of anthropogenic aerosols" (WGI AR5 Chapter 11 ES). In addition, SREX (IPCC, 2012a, Figure SPM.4B) projects a reduction in return period for historical once-in-20-year precipitation events globally (land only) to about once-in-14-year or less by 2046–2065.

With regard to the vulnerability and exposure aspects of risk, SREX reviewed literature on the relationship between changes in these factors and the risk of extreme events (IPCC, 2012a, Sections 4.5.4, 4.5.6). Increases in local vulnerability and exposure to extreme precipitation can lead to a disproportionate increase in overall risk (IPCC, 2012a, Sections 4.3.5.1, 9.2.8; Douglas et al., 2008; Douglas, 2009; Hallegate et al., 2011; Ranger, 2011). For example, growth of megacities both concentrates exposure and vulnerability and can generate "synchronous failure" that spreads beyond the immediate vicinity of extreme events. Megacities increase nighttime temperature extremes via the urban heat island effect (Section 8.2.3.1; IPCC, 2012a, Sections 4.3.5.1, 4.4.5.2) while also enhancing exposure to high air pollution levels (IPCC, 2012a, Sections 4.3.5.1, 9.2.1.2.3; Fang et al., 2013) and consequent health effects (Sections 11.5.3.2, 11.5.3.4), with widespread impacts by mid-century in some studies. Densely populated areas of East and South Asia and North America are projected to be especially affected by climate-related air pollution (Fang et al., 2013).

Projections of the global socioeconomic (Mendelsohn et al., 2012) impact of tropical cyclones demonstrate increasing risk due to interactions of increasing storm intensity with exposure. Hazard projection suggests a disproportionate increase in exposure to tropical cyclone risk with increasing temperature at New York City due to combined effects of storm intensification and sea level rise (Lin et al., 2012). Other studies (Jongman et al., 2012; Hallegate et al., 2013; Preston, 2013) project increasing coastal flood risk due to increasing exposure, although the first two do not disaggregate to specific types of extreme events. Taken together, this evidence supports a conclusion of disproportionate increase in risk associated with extreme events as temperature, and in many cases, exposure and vulnerability increase as well.

Based on the above assessments of the physical hazard alone, we find increased confidence in the AR4 assessment of the risk from extreme weather events. Based on the attribution of heat and precipitation extremes to anthropogenic climate change, the attribution to climate change of impacts of climate extremes on one unique and threatened system, and the current vulnerability of other exposed systems, we assign a yellow level of risk at recent temperatures in Figure 19-4 (*high*

19

confidence), consistent with Smith et al. (2009). We assign a transition to red beginning below 1°C compared to 1986–2005 (also consistent with Smith et al. (2009)) based primarily on the *magnitude* and *likelihood* and *timing* (see Section 19.2.2.2) of the projected change in hazard of extreme weather events, indicating that impacts will become more severe and widespread over the next few decades (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures (*high confidence*).

19.6.3.4. Distribution of Impacts

The distribution of impacts is a category of climate change consequences that includes key risks to particular societies and social-ecological systems that may be disproportionately affected due to unequal distribution of hazards, exposure, or vulnerability. AR4 concluded that there is *high confidence* that low-latitude, less-developed areas are generally at greatest risk and found that, because vulnerability to climate change is also highly variable within countries, some population groups in developed countries are also highly vulnerable even to a warming of less than 2°C above 1990–2000 (Schneider et al., 2007). These conclusions remain valid and are now supported by a limited number of impact studies that explicitly consider differences in socioeconomic conditions that affect vulnerability across regions or populations (Mougou et al., 2011; Müller et al., 2011; Gosling and Arnell, 2013; Schewe et al., 2013). Furthermore, we have increased confidence in the AR4 assessment of the risk arising in the near term from the distribution of impacts from extreme weather events because, by their very nature, these events change in a locally and temporally variable fashion with, for example, a larger change in extreme temperatures at higher latitudes (IPCC, 2012a, Figure SPM.4A).

Impacts of climate change on food security depend on both production and non-production aspects of the food system, including not just yield effects but also changes in the amount of land in production and adjustments in trade patterns (Section 7.1.1). Effects on prices are often taken as an indicator of impacts on food security, and the combined effect of climate and CO_2 change (but ignoring O_3 and pest and disease impacts) appears *about as likely as not* to increase prices by 2050, with few new studies examining prospects at longer time horizons (Section 7.4.4). Most studies have focused on geographical differences in the effects of climate change on crop yields. With regard to such distributional consequences, yields of maize and wheat begin to decline with about 1°C to 2°C of local warming in the tropics, with or without adaptation taken into account (Figure 7-4). Temperate maize and tropical rice yields are less clearly affected at these temperatures, but significantly affected with local warming of 3 to 5°C particularly without adaptation (based on studies with various baselines, see Section 7.3.2.1). These data confirm AR4 findings that even small warming will decrease yields in low-latitude regions (*medium evidence*, *high agreement*; Section 7.3.2.1.1), and increase the risk assigned to yields in mid- to high-latitude regions (compared to AR4), suggesting that temperate wheat yield decreases are *about as likely as not* for moderate warming.

Risks of climate change related to freshwater systems, such as water scarcity and flooding, increase with global mean temperature rise (*medium evidence*, *high agreement*; Chapter 3 ES; Table 3-2). Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*high agreement*, *robust evidence*; Section 3.5; Chapter 3 ES). One study using multiple climate and hydrological models to simulate impacts of scenario RCP8.5 and Shared Socioeconomic Pathway 2 (SSP2) project that global warming of 1.7°C above preindustrial will reduce water resources by more than one standard deviation, or by more than 20%, for 8% of the global population, while for warming of 2.7°C above preindustrial this increases to 14% (model range 10 to 30%), and for warming of 3.7°C above preindustrial it reaches a mean of 17% across models (Schewe et al., 2013). In addition, in another study (Gosling and Arnell, 2013), climate change amplifies water scarcity by 30 to 40% for 1.7 to 2.7°C of warming, with around 40% of the global population under increased water stress. In one model, exposure to water scarcity increases steeply up to 2.3°C above preindustrial in North and East Africa, Arabia, and South Asia (Gosling and Arnell, 2013). In Africa water resources risks are "medium-high" at 2°C and "high-very high" at 4°C (Table 22-6). Model projections generally agree that discharge will decrease in the Mediterranean and in large parts of North and South America (Schewe et al., 2013). However, there are opportunities for adaptation in the water resources sector, particularly for municipal water supply (Section 3.6).

The first global scale analysis of climate change impacts on almost 50,000 species of plants and animals has highlighted that risks are not distributed equally, with sub-Saharan Africa, Central America, Amazonia, and Australia at risk for plants and animals, and North Africa, Central Asia, and southeastern Europe for many plants (Warren et al., 2013a). A traits-based analysis of more than 16,000 species identified Amazonia and Mesoamerica as being at risk for birds and amphibians; central Eurasia, the Congo Basin, the Himalayas, and Sundaland for birds; and the Coral Triangle region for corals (Foden et al., 2013).

In summary, since AR4, new evidence has emerged highlighting the *magnitude* of risk for particular regions, for example, in relation to the potential for regional impacts on ecosystems (see Section 19.6.3.2), megadeltas (see Section 8.2.3.3; Chapter 5), and agricultural systems, which is exacerbated by the potential for changes in the monsoon systems (see WGI AR5 Sections 12.5.5, 14.2). Overall there is increased evidence that low-latitude and less developed areas generally face greater risk than higher latitude and more developed countries (Smith et al., 2009). At the same time, there has been an increase in appreciation for vulnerability (e.g., to extreme events) in developed countries, especially, localized issues of differential vulnerability in particular areas of the developed world (IPCC, 2012a, Section 2.5.1.2).

Regionally differentiated impacts on crop production have been detected and attributed to climate change with *medium* to *high confidence* (Section 18.4.1.1), and we interpret this as an early warning sign of attributable impacts on food security. For this reason, as well as for reasons of *timing* and *likelihood* and *magnitude* of these risks, we assign a yellow level of risk at recent temperatures in Figure 19-4. Based on risks to regional crop production and water resources the transition from yellow to red is assessed to occur between 1°C and 2°C above the 1986–2005 global mean temperature (*medium confidence*). Both assessments are consistent with Smith et al. (2009). Furthermore, given evidence that agronomic adaptations would be more than offset for tropical wheat and maize where increases in local temperature of more than 3°C above preindustrial occur (*limited evidence*, *medium agreement*; Chapter 7 ES; Section 7.5.1.1.1; Figure 7-4), the intensity of red increases nonlinearly toward purple in recognition of the temperature sensitivity of crop productivity and limited efficacy of agronomic adaptation above 2°C compared to 1986–2005.

19.6.3.5. Global Aggregate Impacts

The RFC pertaining to aggregate impacts includes risks that are aggregated globally into a single metric, such as monetary damages, lives affected, lives lost, or species or ecosystems lost. Estimates of the aggregate, economy-wide risks of climate change since AR4 continue to exhibit a *low level of agreement*. Studies at the sectoral level have been refined with new data and models, and have assessed new sectors.

AR4 stated with *medium confidence* that approximately 20 to 30% of the plant and animal species assessed to date are likely at increasing risk of extinction as global mean temperatures exceed a warming of 2°C to 3°C above preindustrial levels (Fischlin et al., 2007). There is *high confidence* that climate change will contribute to increased extinction risk for terrestrial, freshwater, and marine species over the coming century (Sections 4.3.2.5, 30.5; Box CC-CR). Since AR4 a substantial amount of additional work has been done, looking at many more species and using new and/or improved modeling and traits-based techniques, strengthening the evidence of increasing risk of extinction with increasing temperature (e.g., Lenoir et al., 2008; Amstrup et al., 2010; Hunter et al., 2010; Bálint et al., 2011; Pearman et al., 2011; Barnosky et al., 2012; Bellard et al., 2012; Norberg et al., 2012; Foden et al., 2013). More studies have scrutinized caveats to previous studies and assessed their role in either under- or overestimating extinction risks (e.g., Beale et al., 2008; Cressey, 2008; Randin et al., 2009; He and Hubbell, 2011; Harte and Kitzes, 2012), including the role of evolution (Norberg et al., 2012), while others have carefully examined risk considering other species traits (looking at exposure, sensitivity, and potential adaptive capacity for large numbers of species; Foden et al., 2013). Literature incorporating multiple new assessment techniques quantifying extinction risks supports the conclusion that the dependence between increasing extinction risk and temperature is *robust* (*medium confidence*), albeit varying across biota. However, there is *low agreement* on assigning specific numerical values for species at risk (Sections 19.3.2.1, 19.5.1). Since AR4 it has been found that not only endemics (which have tended to be the focus of many previous studies) but species geographically widespread are at risk (Warren et al., 2013a), implying a significant and widespread potential loss of ecosystem services (Section 4.3.2.5; Gaston and Fuller, 2008; Allesina et al., 2009; Staudinger et al., 2012), comprising a new emergent risk (Table 19-4). At a global temperature rise of 3.5°C to 4°C above preindustrial, Foden et al. (2013) estimated that 30 to 60% of the birds and amphibians and 40 to 62% of the corals studied are highly vulnerable to climate change. Taking this estimate conservatively as a maximum (i.e., assuming all species not studied are able to adapt at least as well as the groups investigated), and combining this estimate with the finding of ≥50% loss of potential range in 57% of plants and 34% of animals studied globally for a global temperature rise of 3.5°C to 4°C by the 2080s allowing for realistic dispersal rates (Warren et al., 2013a), there is *high confidence* that climate change will significantly affect biodiversity and related ecosystem services.

Much new work has focused on future projected synergistic impacts of climate change-induced increases in fire, drought, disease, and pests (Flannigan et al., 2009; Hegland et al., 2009; Koeller et al., 2009; Krawchuk et al., 2009; Garamszegi, 2011). New work has demonstrated that the expected large turnovers of more than 60% in marine species assemblages by the 2050s in response to climate change (under SRES scenarios A1B and B1), combined with shrinkage of fish body weight of 14 to 24% (SRES A2; Cheung et al., 2009, 2013), put marine ecosystem functioning at risk with negative consequences for fishing industries, coastal communities, and wildlife that are dependent on marine resources (Lam et al., 2012).

Consistent with AR4, global aggregate economic impacts from climate change are highly uncertain, with most estimates a small fraction of gross world product up until at least 2.5°C of warming above preindustrial (Section 10.9.2; Figure 10-1). Some studies suggest net benefits of climate change at 1°C of warming (Section 10.9.2; Figure 10-1). Little is known about global aggregate damages above 3°C (Sections 10.9.2, 19.5.1; Figure 10-1; Ackerman et al., 2010; Weitzman, 2010; Ackerman and Stanton, 2012; Kopp et al., 2012). Aggregate damages vary with alternative development pathways, but the relationship between development pathway and aggregate damages is not well explored. In many sectors, damages as a fraction of output are expected to be larger in low-income economies, although monetized damages are expected to be larger in high-income economies (e.g., Anthoff and Tol, 2010). Adaptation is treated differently across modeling studies (Hope, 2006; de Bruin et al., 2009; Bosello et al., 2010; Füssel, 2010; Patt et al., 2010) and affects aggregate damage estimates in ambiguous ways.

Estimates of global aggregate economic damages omit a number of factors (Yohe and Tirpak, 2008; Kopp and Mignone, 2012). While some studies of aggregate economic damages include market interactions between sectors in a computable general equilibrium framework (e.g., Bosello et al., 2012a; Roson and van der Mensbrugghe, 2012), none treat non-market interactions between impacts (Warren, 2011), such as the effects of the loss of biodiversity among pollinators and wild crops on agriculture or the effects of land conversions owing to shifts in agriculture on terrestrial ecosystems (see Sections 19.3-4). They do not include the effects of the degradation of ecosystem services by climate change (Section 19.3.2.1) and ocean acidification (Section 19.5.2), and in general assume that market services can substitute perfectly for degraded environmental services (Sterner and Persson, 2008; Weitzman, 2010; Kopp et al., 2012). The global aggregate damages associated with large-scale singular events (Section 19.6.3.6) are not well explored (Kopp and Mignone, 2012; Lenton and Ciscar, 2013).

The risk associated with global aggregate impacts is similar to that expressed in AR4 and Smith et al. (2009), as indicated in Figure 19-4, with risk based primarily on economic damages and confidence in the assessment unchanged. For aggregate economic impacts, there is *low* to *medium confidence* in attribution of climate change influence on a few sectors (Section 18.6.4; Table 18-11) so that this RFC is still shaded white at recent temperature in Figure 19-4. Risks of global aggregate impacts are moderate for additional warming between 1°C to 2°C compared to 1986–2005, reflecting impacts to both Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss with associated loss of ecosystem goods and services results in high risks around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*) but few quantitative estimates have been completed for additional warming around 3°C or above.

19.6.3.6. Large-Scale Singular Events: Physical, Ecological, and Social System Thresholds and Irreversible Change

Large-scale singular events (sometimes called "tipping points," or critical thresholds) are abrupt and drastic changes in physical, ecological, or social systems in response to smooth variations in driving forces (Smith et al., 2001, 2009; McNeall et al., 2011). Combined with widespread vulnerability and exposure, they pose key risks because of the potential magnitude of the consequences; the rate at which they would occur; and, depending on this rate, the limited ability of society to cope with them. Research on the societal impacts associated with such events is limited; we focus in this section on physical hazards and ecological thresholds.

Regarding singular events in physical systems, AR4 expressed *medium confidence* that at least partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic ice sheet (WAIS), would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1°C to 4°C (relative to 1990–2000), causing a contribution to sea level rise of 4 to 6 m or more (Schneider et al., 2007). Studies since AR4 are consistent with these judgments but provide a more detailed view (see WGI AR5 Chapter 13). The Greenland ice sheet (*very likely*) and the Antarctic ice sheet (*medium confidence*) contributed to the 5 m higher than present (*very high confidence*) to 10 m above present (*high confidence*) sea level rise that occurred during the Last Interglacial (WGI AR5 SPM; Kopp et al., 2009; McKay et al., 2011; Dutton and Lambeck, 2012). This period provides a partial analog for the magnitude of mid- to late-21st century warming because GMT was not more than 2°C warmer than preindustrial (*medium confidence*; WGI AR5 SPM; Section 5.3.4). However, the resulting sea level rise may have taken millennia to complete.

With regard to projection, WGI AR5 finds that "There is *high confidence* that sustained warming greater than some threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea level rise of up to 7 m. Current estimates indicate that the threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) global mean warming with respect to preindustrial" (WGI AR5 SPM). A threshold for the disintegration of WAIS remains difficult to identify due to shortcomings in various aspects of ice sheet modeling, including representation of the dynamical component of ice loss and ocean processes. For RCP8.5, projected sea level rise is 1 to more than 3 m (*medium confidence*) by 2300. Beyond 2300, "Sustained mass loss by ice sheets would cause larger sea level rise, and some part of the mass loss might be irreversible" (WGI AR5 SPM). Extreme exposure and vulnerability to the *magnitude* of sea level rise associated with loss of a significant fraction of either ice sheet is found worldwide (Nicholls and Tol, 2006) but millennial time scales for ice loss allow greater opportunities to adapt successfully than do century scales, so *timing* is a critical and highly uncertain factor in assessing the risk.

There is also additional evidence regarding singular events in other physical systems. Feedback processes in the Earth system could cause accelerated emissions of CH_4 from wetlands, permafrost, and ocean hydrates. There are large uncertainties in the size of carbon stores, the time scales of release, and the fate of the carbon once released. The probability of substantial carbon release in the form of CH_4 or CO_2 increases with warming (Archer et al., 2009; O'Connor et al., 2010). WGI AR5 finds "*low confidence* in modelling abilities to simulate transient changes in hydrate inventories, but large CH_4 release to the atmosphere during this century is *unlikely*" (WGI AR5 Section 6.4.7.3). Owing to such uncertainties, the existence of a tipping point cannot be ascertained.

AR4 stated that Arctic summer sea ice disappears almost entirely in some projections by the end of the century (WGI AR4 Section 10.3); WGI AR5 finds that a "nearly ice-free Arctic Ocean (sea ice extent less than 1×10^6 km^2 for at least 5 consecutive years) in September before mid-century is *likely* under RCP8.5 (*medium confidence*)." Furthermore, "There is little evidence in global climate models of a tipping point (or critical threshold) in the transition from a perennially ice-covered to a seasonally ice-free Arctic Ocean beyond which further sea ice loss is unstoppable and irreversible" (WGI AR5 Chapter 12 ES). Whether or not the physical process is reversible, effects of ice loss on biodiversity may not be.

Large uncertainties remain in estimating the probability of a shutdown of the AMOC. One expert elicitation finds the chance of a shutdown to be between 0 and 60% for global average warming between 2°C and 4°C, and between 5 and 95% for 4°C to 8°C of warming relative to 2000 (Zickfeld et al., 2007; Kriegler et al., 2009). AR5 judges that "It is *very unlikely* that the AMOC will undergo an abrupt transition or collapse in the 21st century for the scenarios considered. There is *low confidence* in assessing the evolution of the AMOC beyond the 21st century because of the limited number of analyses and equivocal results. However, a collapse beyond the 21st century for large sustained warming cannot be excluded" (WGI AR5 SPM).

Regarding regime shifts in ecosystems, there are "early warning signs" from detection and attribution analysis that both Arctic and warmwater coral reef systems are experiencing irreversible regime shifts (Section 18.6.4). Recent observational evidence confirms the susceptibility of the Amazon to drought and fire (Adams et al., 2009; Phillips et al., 2009), and recent improvements to models provide increased confidence in the existence of a tipping point in the Amazon from humid tropical forest to seasonal forest or grassland as the dominant ecosystem (Jones et al., 2009; Lapola et al., 2009; Malhi et al., 2009; Section 4.3.3.1; Figure 4-8; Box 4-3). In contrast, one recent study suggests that the Amazon may be less susceptible to crossing a tipping point than previously thought (Cox et al., 2013), although this is contingent on the uncertain role of CO_2 fertilization being as strong as models project. Overall, recent "multi-model estimates based on different CMIP3 climate scenarios and different dynamic global vegetation models predict a moderate risk of tropical forest reduction in South America and even lower risk for African and Asian tropical forests" (WGI AR5 Section 12.4.8.2).

Based on the weight of the above evidence, we judge that the overall risk from large-scale singular events is somewhat higher than assessed in AR4 and indicated by Smith et al. (2009). The position of the transition from white to yellow between 0°C and 1°C compared to 1986–2005 remains as before but with higher confidence due to the existence of early warning signs regarding regime shifts in Arctic and warmwater coral reef systems. The transition from yellow to red occurs over a range from 1°C to more than 3°C, consistent with Smith et al. (2009) and based primarily on the uncertainty in the warming level associated with eventual ice sheet loss. However, we assess a faster increase in risk as temperature increases between 1°C and 2°C compared to 1986–2005, largely determined by the risk arising from a very large sea level rise due to ice sheet loss as occurred during the Last Interglacial when GMT was no more than 2°C warmer than preindustrial (*medium confidence*; WGI AR5 Sections 5.3.4, 5.6.2). This assessment of risk is based primarily on the *magnitude* and *irreversibility* of such sea level rise and the widespread exposure and vulnerability to it. However, as noted, the slower the rate of rise, the more feasible becomes adaptation to reduce vulnerability and exposure. Owing to this uncertainty in *timing*, we refrain from imposing a transition to purple in Figure 19-4.

19.7. Assessment of Response Strategies to Manage Risks

The management of key and newly identified risks of climate change can include mitigation that reduces the likelihood of climate changes and physical impacts and adaptation that reduces the exposure and vulnerability of society and ecosystems to both. Key risks, impacts, and vulnerabilities to which societies and ecosystems may be subject will depend in large part on the mix of mitigation and adaptation measures undertaken, as will the evaluation of RFCs (Section 19.6.3). This section therefore assesses relationships between mitigation, adaptation, and the residual impacts that generate key risks. It also considers limits to both mitigation and adaptation responses, because understanding where these limits lie is critical to anticipating risks that may be unavoidable. Potential impacts involving thresholds for large changes in physical, ecological, and social systems (Section 19.6.3.6) are particularly important elements of key risks, and the section therefore assesses response strategies aimed at avoiding them or adapting to crossing them.

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19.7.1. Relationship between Adaptation Efforts, Mitigation Efforts, and Residual Impacts

Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable (*very high confidence*). Evaluating potential mixes of mitigation, adaptation, and impacts requires joint consideration of outcomes for climate change and socioeconomic development. A principal way in which these different mixes are assessed is comparing the impacts that result from scenarios with little or no mitigation (and therefore more climate change) to those with substantial mitigation (and less climate change). Climate change mitigation costs have been extensively explored (WGIII AR5 Chapter 6), but there has been less work on quantifying the impacts avoided by mitigation and, with the exception of studies of the impacts of sea level rise (Nicholls et al., 2011), treatment of adaptation has been limited and uneven. In this section, unless otherwise stated, global temperature rise is given relative to preindustrial (1850–1900) levels.

Impact studies generally indicate that mitigation can reduce a large proportion of climate change impacts that would otherwise occur (*high confidence*). In one study, mitigation that stabilizes global CO_2 concentrations at 550 ppm reduces by 80 to 95% the number of people additionally at risk of hunger (largely in Africa) in 2080 under an SRES A2 scenario with CO_2 concentrations of 800 ppm, creating an estimated benefit of US$23 to 34 billion of agricultural output compared to the un-mitigated case (Tubiello and Fischer, 2007). In Africa, there are much greater impacts on crop productivity, freshwater resources, and ecosystems at 4°C than at 2°C, with adaptation failing to reduce risk below a "high" level at 4°C ("very high" for crop productivity), whereas at 2°C risks are lower and adaptation could reduce these risks to a "medium" level (Table 22-6). In North America, with 4°C warming, adaptation is not expected to reduce risks below "high" for urban flooding (both riverine and coastal) or for fire damage in ecosystems, or below "medium" for heat-related human mortality. Without adaptation, risk is "very high" for these sectors. In contrast, at 2°C risks are at the "high" level for urban flooding and heat-related human mortality, but the risk of fire in ecosystems is still "very high." At 2°C, adaptation is expected to reduce urban flooding risk to "medium" and heat-related human mortality risk to "low" (Table 26-1). Impacts on water resources would also be reduced (Table 3-2). Fung et al. (2011) and Gosling and Arnell et al. (2013) both found that climate change-induced increases in water stress (defined as persons with <1700 or <1000 m^3 per capita per year respectively in the two studies) globally would be reduced significantly were global temperature rise to be constrained to 2°C rather than 4°C. Reducing climate change from an RCP8.5 scenario to an RCP2.6 scenario reduces the proportion of the global population that experiences >10% declines in available groundwater from 27 to 50% to 11 to 39% (Portmann et al., 2013).

Figure 19-6 highlights results from three studies that estimated the global avoided impacts for multiple sectors when global average temperature is limited to 2°C rather than following scenarios with no mitigation, such as the SRES A1B or A1FI baseline scenarios in which global average temperature reaches 4°C and 5.6°C, respectively (Arnell et al., 2013; Warren et al., 2013a,b). The studies isolate the effects of climate change by using common socioeconomic assumptions in mitigation and baseline scenarios. Overall, sector-specific impacts were reduced by 20 to 80%, with aggregate global economic damages reduced by about one-half (Warren et al., 2013b). The largest impacts avoided were for crop productivity, drought in cropland, biodiversity, exposure to coastal and pluvial flooding, and energy use for cooling, while avoided impacts were smaller for water resources stress. Because some areas become wetter and others drier (WGI AR5 Section 12.4.5), there are regions where climate change results in decreases in flood, drought, or water stress, which may be beneficial. (Note that reduced water stress is not necessarily beneficial; for example, if increased precipitation occurs in a small number of isolated heavy rainfall events, water cannot easily be stored and can cause flooding). This means that as well as avoiding a large amount of negative impacts, mitigation is projected to result in the avoidance of some benefits that are projected to result from climate change, although these avoided benefits are much smaller than the avoided impacts. There are shown as the blue bars in Figure 19-6. Avoided impacts are significantly larger when an A1FI baseline is used compared to an A1B baseline (Figure 19-6) because emissions and global temperature rise are greater in the A1FI baseline scenario. All of these studies employed an ensemble of climate change projections based on emulation of seven different Global Climate Models (GCMs). The proportion of impacts avoided at the global scale was relatively robust to uncertainties in regional climate projection, but the magnitude of avoided impacts varied considerably with climate projection uncertainty.

The timing of emissions reductions strongly affects impacts. In general fewer impacts can be avoided when mitigation is delayed (Arnell et al., 2013; Warren et al., 2013a,b; Figure 19-6b) because there are limits to how fast emissions can be reduced subsequently to compensate for the delay (Section 19.7.2). For example, if global emissions peak in 2016 and are then reduced at 5% annually, one half of global aggregate economic

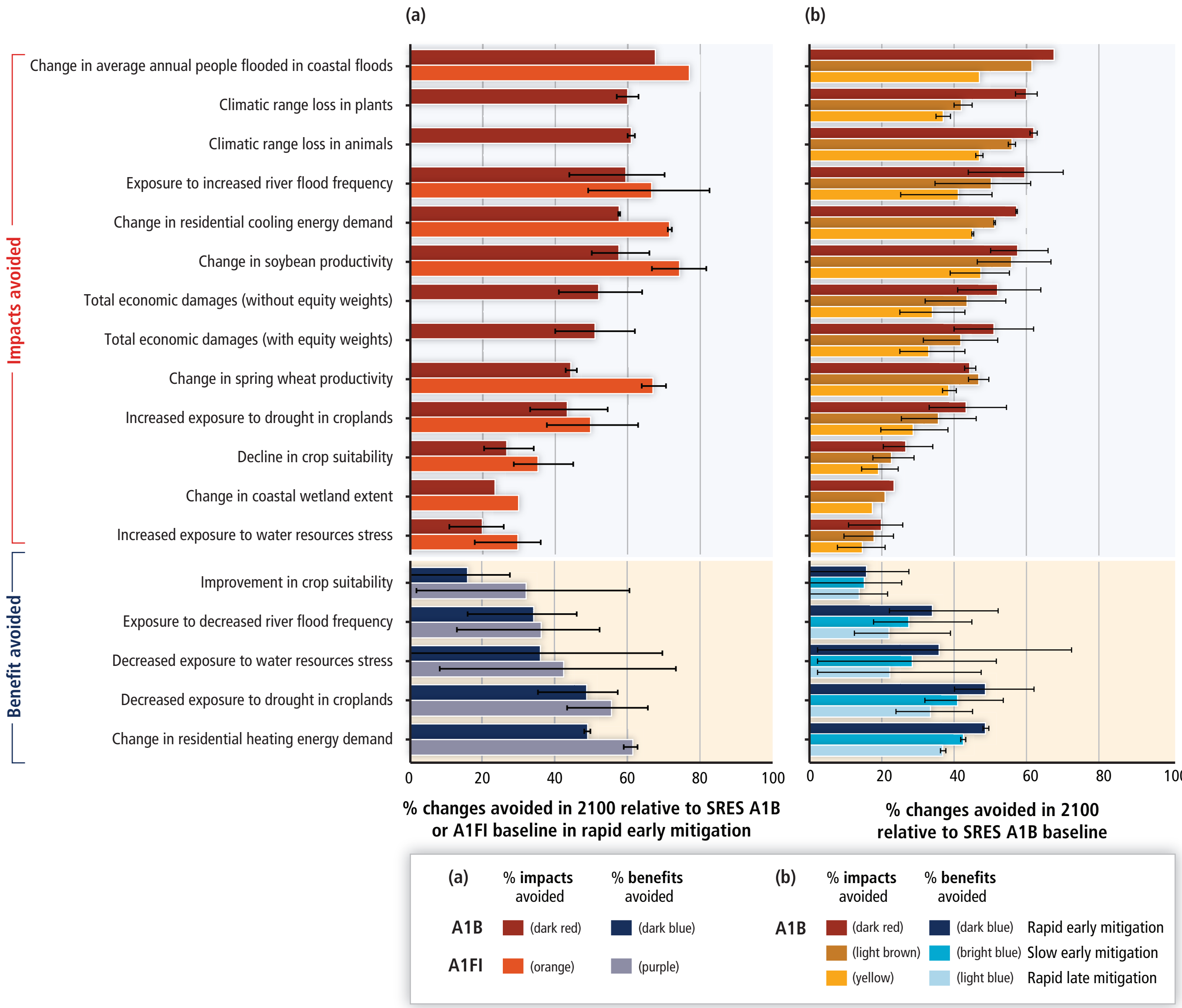

Figure 19-6 | (a) Climate change impacts avoided by an early, rapid mitigation scenario in which global emissions peak in 2016 and are reduced at 5% thereafter, compared to two no-mitigation baseline cases, Special Report on Emission Scenarios (SRES) A1B (dark red bars) and SRES A1FI (orange bars). Impacts avoided are larger if the A1FI baseline scenario is used than if the A1B baseline is used, because greenhouse gas emissions in A1FI exceed those in A1B (see Section 19.7.1). Since the literature does not provide estimates of avoided impacts relative to the A1FI baseline for all sectors considered here, some bars are absent from the panel (a). (b) The dependence of the potential to avoid climate change impacts upon the timing of emission reductions is illustrated. Climate change impacts avoided by the same early, rapid mitigation scenario compared to the no-mitigation baseline case SRES A1B (dark red bars) are shown. The information displayed is identical to the orange bars in (a), but a comparison is now made with the impacts avoided from two other less stringent mitigation scenarios. Impacts avoided if global emissions peak in 2016 but are subsequently reduced more slowly (2% annually) are lower (light brown bars compared to dark red bars). However, if mitigation occurs later, so that global emissions do not peak until 2030, even if emissions are subsequently reduced at 5% annually, the avoided impacts are smaller than in either of the other two cases (yellow bars compared to dark red and light brown bars). Both panels show the uncertainty range (error bars) due to regional climate change projected with seven global climate models. Errors due to uncertainty within impacts models are not shown. Uncertainties associated with sea level rise related impacts are not provided because the models used a single sea level rise projection. Because increases and decreases in water stress, flood risks, and crop suitability are not co-located and affect different regions, these effects are not combined. Since some areas become wetter and others drier (WGI AR5 Section 12.4.5), there are regions where climate change results in decreases in flood, drought, or water stress, which may be beneficial. This means that avoided benefits of climate change, as well as avoided impacts of climate change, are also shown here, as the shorter blue bars. Overall the avoided impacts greatly outweigh the avoided benefits (Arnell et al., 2013; Warren et al., 2013a,b).

impacts might be avoided (Figure 19-6b, orange bars), or around 43% if emissions are reduced more slowly at 2% annually (Figure 19-6b, pink bars); compared to only one-third if emissions peak in 2030 even if emissions are reduced at 5% thereafter (Warren et al., 2013b, Figure 19-6b, brown bars). This applies irrespective of whether or not equity weighting is used in the impact valuation process.

Avoided impacts vary significantly across regions as well as sectors (*high confidence*) due to (1) differing levels of regional climate change, (2) differing numbers of people and levels of resources at risk in different regions, and (3) differing sensitivities and adaptive capacities of humans, species, or ecosystems (Tubiello and Fischer, 2007; Ciscar et al., 2011; Arnell et al., 2013; Section 25.10.1). The length of time it takes for avoided impacts to accrue is determined partly by the nature of the climate system. Benefits accrue least rapidly for impacts associated with sea level rise such as coastal flooding and loss of mangroves and coastal wetlands because sea level rise responds very slowly to mitigation efforts (Meehl et al., 2012). Nevertheless, mitigation may limit 21st century impacts of increased coastal flood damage, dry land loss, and wetland loss substantially (*limited evidence*, *medium agreement*) albeit there is *little agreement* on the exact magnitude of this reduction (Section 5.4.3.1). Benefits accrue more rapidly for impacts associated with global temperature change (WGI AR5 Section 12.5.2, Figure 12.44) and those associated with reduced ocean acidification because surface pH responds relatively quickly to changes in emissions of CO_2 (FAQ 30.1).

In WGIII AR5 Chapter 6, the emission scenarios in the literature (as collected in the AR5 database) have been categorized on the basis of the 2100 radiative forcing (in a total of seven categories). Most Integrated Assessment Models (IAMs) provide information on concentration, forcing, and temperature. However, as the climate components of the IAMs differ, all scenarios were reanalyzed in the simple climate model Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC; Meinshausen et al., 2011) using its probabilistic set-up. The results of this categorization can be used to connect emission trajectories to climate outcomes (Figure 19-7a) and impacts and risks (Figure 19-7b; Table 19-4).

Mitigation scenarios in category 1 with a 2100 CO_2-eq concentration of 430 to 480 ppm result in a median projected 2100 global temperature rise of between 1.5°C and 1.7°C above preindustrial (10–90% range 1.0–2.8°C) (Figure 19-7a; WGIII AR5 Table 6.3). These scenarios correspond to a 2011–2100 cumulative emission level of around 630–1180 $GtCO_2$ (WGIII AR5 Table 6.3). Under these scenarios, based on the MAGICC calculations, warming is *likely* to stay below 2°C and *very likely* to stay below 3°C during the 21st century. This significantly reduces the key risks listed in Table 19-4, as well as others discussed in this chapter. Constraining global temperature rise to 2°C would constrain the risks associated with global aggregate impacts and large-scale singular events to the yellow or moderate level and the risks associated with the distribution of impacts, extreme weather events, and to unique and threatened systems to the lower part of the red or high level. If global

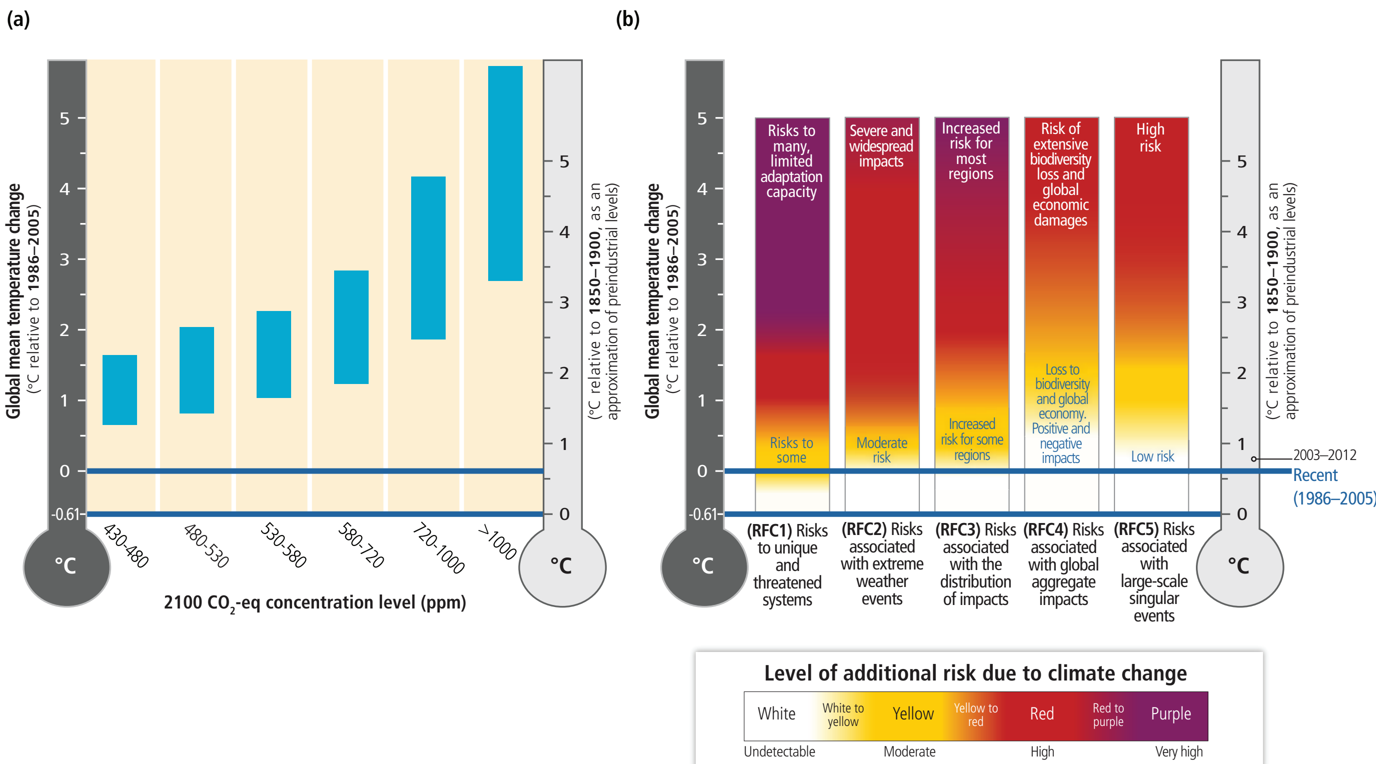

Figure 19-7 | Relationship between mitigation scenario categories considered in WGIII AR5, in terms of their CO_2-eq concentrations and global temperature rise outcomes in 2100, and level of risk associated with Reasons for Concern. (a) The projected increase in global mean temperature in 2100 compared to pre-industrial and recent (1986–2005), calculated using the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) climate model for the scenario categories defined in WGIII AR5 Chapter 6, indicating the uncertainty range resulting both from the range of emission scenario projections within each category (10–90th percentile) and the uncertainty in the climate system as represented by MAGICC (16–84th percentile) (data taken from WGIII AR5 Chapter 6). (b) Reproduction of Figure 19-4 for ease of comparison. Beyond 2100, temperature, and therefore risk, decreases in most of the lowest three scenarios and increases further in most of the others.

temperature rise were 1.5–1.7°C only, risks to unique and threatened systems and risks associated with extreme weather events would be further constrained to the transition between moderate and high risk levels. The temperature levels in the RCP2.6 scenario are 1.2°C to 2.0°C (WGI AR5 Table 12.2) matching closely the scenarios in this category.

Mitigation scenarios in category 2 with a concentration of 480 to 530 ppm CO_2-eq in 2100 correspond to a median projected 2100 global temperature rise of between 1.7°C and 2.1°C (10–90% range 1.2–3.3°C) in the MAGICC calculations. These scenarios correspond to a cumulative emission level over the 2011–2100 period on the order of 960–1550 $GtCO_2$ (WGIII AR5 Table 6.3) and are *as likely as not* to stay below 2°C, but are still *very unlikely* to rise above 3°C. Thus, scenarios in category 2 also reduce risks, but to a lesser extent than for category 1. If global temperature rise reaches 2.5°C in 2100, levels of risk due to extreme weather events are at the red or high level, while those to unique and threatened systems now reach the very high or purple level reflecting inability to adapt. Risks associated with global aggregate impacts reach the transition zone from yellow or moderate level to red or high risk, while risks associated with the distribution of impacts and large-scale singular events reach the red or high level.

Mitigation scenarios in category 3 with 530 to 580 ppm CO_2-eq in 2100 correspond to a median projected temperature rise of between 2.0°C and 2.3°C (range 1.4–3.6°C) above preindustrial levels (WGIII AR5 Table 6.3) such that it is *very unlikely* that temperature rise would stay below 1.5°C, and less probable than category 2 to remain below 2°C, affording little protection to coral reefs. In this category, risks to unique and threatened systems remain high or very high indicating inability to adapt. Risks associated with extreme weather events remain at the high level. Risks associated with the distribution of impacts, global aggregate impacts and large-scale singular events range from moderate to high.

Mitigation scenarios in category 4 with 580 to 720 ppm CO_2-eq in 2100 result in a range of possible temperature outcomes between 2.3°C and 2.9°C (10–90% range 1.5–4.5°C) above preindustrial levels, affording no protection to coral reefs. In these scenarios, it is *more likely than not* that global temperature rise would exceed 2°C (WGIII AR5 Table 6.3) so that risks to unique and threatened systems remain high or very high indicating inability to adapt. Risks associated with extreme weather events and the distribution of impacts are high. Levels of risk associated with global aggregate impacts and large-scale singular events may be moderate or high (*high confidence*). Global temperature rise in RCP4.5 in 2100 is 1.9 to 2.9°C above preindustrial levels (WGI AR5 Table 12.2), matching the low scenarios in this category.

Onset of large-scale dissolution of coral reefs is projected if CO_2 concentrations reach 560 ppm (Sections 5.4.1.6, 5.4.2.4, 19.6.3.2, 26.4.3.2; Silverman, 2009), due to the combined effects of warming and ocean acidification. However, already at 450 ppm, reef growth rates are projected to be reduced by more than 60% globally and by at least 20% globally at 380 ppm (Silverman, 2009). Coral organisms themselves are projected to be damaged by warming at concentrations below 560 ppm: specifically, even with optimistic assumptions regarding the ability of corals to rapidly adapt to thermal stress, RCP4.5 is projected to result in long-term degradation of two-thirds of coral reefs, compared with one-third of them under RCP3PD (Box CC-CR). Hence, maintenance of moderately healthy coral reefs is consistent only with scenarios in the scenarios in the 430 to 480 ppm CO_2-eq category; while some reef protection is achieved with scenarios in the category 480 to 530 ppm CO_2-eq. A low level of protection exists for the category 530 to 580 ppm CO_2-eq while all other categories exceed the 560 ppm level.

Finally, scenarios in category 6 with a concentration level of >1000 ppm CO_2-eq are projected to result in median 2100 temperature rise of 4.1°C to 4.8°C (range 2.8–7.8°C) above preindustrial with negligible chances to constrain it below 2°C above preindustrial (Figure 19-7a) and would allow significant key risks to persist in all the areas listed in Table 19-4. Risk is at the red level for all RFCs except unique and threatened systems, where risk is at the purple level indicating infeasibility of adaptation. For the distribution of impacts, risk reaches the transition to purple if temperatures rise in excess of 4°C above preindustrial levels. For the scenarios with a concentration level between 720 ppm and 1000 ppm (category 5) outcomes for risk levels are high or very high, except that risk of global aggregate impacts ranges from the transition zone from moderate risk up to high risk.

Scenarios with rapid, early mitigation (particularly those with a 2100 CO_2-eq concentration of 430 to 480 ppm) generally delay the onset of a given global annual mean temperature rise until several decades later in the century than is the case for scenarios with slower, delayed mitigation or no mitigation (such as those with a 2100 CO_2-eq concentration of 720 to 1000 ppm), thus allowing impacts to be further reduced by adaptation during this time.

19.7.2. Limits to Mitigation

Mitigation possibilities, such as those implicit in scenarios discussed in Section 19.7.1, are not unlimited. Assessment of maximum feasible mitigation (and lowest feasible emissions pathways) must account for the fact that feasibility is a subjective concept encompassing technological, economic, political, and social dimensions (Hare et al., 2010). Most mitigation studies have focused on technical feasibility, for example, demonstrating that it is possible to reduce emissions enough to have at least a 50% chance of limiting warming to less than 2°C relative to preindustrial (den Elzen and van Vuuren, 2007; Clarke et al., 2009; Edenhofer et al., 2010; Hare et al., 2010; O'Neill et al., 2010), taking into account uncertainty in climate and carbon cycle response to emissions (see WGI AR5 Section 12.5.4 for a discussion of uncertainties in the relationship between emissions and long-term climate stabilization targets). RCP2.6, based on an integrated assessment model-based mitigation scenario (van Vuuren et al., 2012), is *unlikely* to produce more than 2°C of warming relative to preindustrial (*medium confidence*; WGI AR5 Section 12.4.1.1). Such scenarios lead to pathways in which global emissions peak within the next 1 to 2 decades and decline to 50 to 85% below 2000 levels by 2050 (or 40 to 70% compared to 1990 levels), and in some cases exhibit negative emissions before the end of the century (den Elzen et al., 2007, 2010; IPCC, 2007b; van Vuuren et al. 2012). Very few integrated assessment model-based scenarios in the literature demonstrate the feasibility of limiting warming to a maximum of 1.5°C with at least 50% likelihood (Rogelj et al., 2012); most 1.5°C scenarios have been based on stylized emissions pathways (Hare et al.., 2010;

Ranger et al., 2012). The highest emission reduction rate considered in most integrated modeling studies that attempt to minimize mitigation cost is typically between 3 and 4% but with larger values not ruled out although some studies find that for an additional cost higher rates may be achievable (den Elzen et al., 2010; O'Neill et al., 2010).

However, most studies of feasibility include a number of idealized assumptions, including availability of a wide range of mitigation technologies such as carbon capture and storage (CCS) and large-scale renewable and biomass energy. Most also assume universal participation in mitigation efforts beginning immediately, economically optimal reductions (i.e., reductions are made wherever they are cheapest), and no constraints on policy implementation. Any deviation from these idealized assumptions can significantly limit feasible mitigation reductions (Knopf et al., 2010; Rogelj et al., 2012). For example, delayed participation in reductions by non-Organisation for Economic Co-operation and Development (OECD) countries made concentration limits such as not exceeding 450 ppm CO_2-eq (roughly consistent with a 50% chance of remaining below 2°C relative to preindustrial), and in some cases even 550 ppm CO_2-eq, unachievable in some models unless temporary overshoot of these targets (Izrael and Semenov, 2006) were allowed (Clarke et al., 2009), but not in others (Waldhoff and Fawcett, 2011). Technology limits, such as unavailability of CCS or limited expansion of renewables or biomass, makes stabilization at 450 ppm CO_2-eq (or 2°C with a 50% chance) unachievable in some models (Krey and Riahi, 2009; van Vliet et al., 2012). Similarly, if the political will to implement coordinated mitigation policies within or across a large number of countries were limited, peak emissions and subsequent reductions would be delayed (Webster, 2008).

These considerations have led some analysts to doubt the plausibility of limiting warming to 2°C (Anderson and Bows, 2008, 2011; Tol, 2009). "Emergency mitigation" options have also been considered that would go beyond the measures considered in most mitigation analyses (Swart and Marinova, 2010). These include drastic emissions reductions achieved through limits on energy consumption (Anderson and Bows, 2011) or geoengineering through management of the Earth's radiation budget (Section 19.5.4; WGI AR5 Chapters 6, 7).

19.7.3. Avoiding Thresholds, Irreversible Change, and Large-Scale Singularities in the Earth System

Section 19.6.3.6 discussed the RFC related to nonlinear changes in the Earth system ("large-scale singular events"), whereby anthropogenic forcings might cause irreversible and potentially rapid transitions over a wide range of time scales (see Section 19.6.3; WGI AR5 SPM, TS, TFE.5, Section 12.5; Lenton et al., 2008). The risk of triggering such transitions generally increases with increasing anthropogenic climate forcings/ climate change (Lenton et al., 2008; Kriegler et al., 2009; Levermann et al., 2012). Reducing GHG emissions is projected to reduce the risks of triggering such transitions (*medium confidence*). Adaptation could reduce their potential consequences, but the efficacy of adaptation might be limited, for example for rapid transitions (Section 19.7.5).

Several studies have sought to identify levels of atmospheric GHG concentrations or global average temperature change that would limit the risks of triggering these transitions (e.g., Keller et al., 2005, 2008; Lenton et al., 2008; Kriegler et al., 2009). Section 19.6.3.6 assesses evidence regarding the relationship between global average temperature and risks of disintegration of major ice sheets, loss of Arctic sea ice, shutdown of the AMOC, carbon releases from temperature-related feedback processes, and regime shifts in ecosystems. Additional aspects of these risks are important to mitigation strategies. For example, it is important to distinguish between triggering and experiencing a threshold response because model simulations suggest that there can be sizable delays between the two (e.g., Lenton et al., 2008). The location of these trigger points can be difficult to determine from process-based models alone, as some of these models lack potentially important processes (see e.g., WGI AR5 Chapter 13).

In this situation, expert elicitations can provide additional useful information for risk assessments. One such assessment based on expert elicitation (Lenton et al., 2008) finds that limiting global mean temperature increase to approximately 3°C above recent (1980–1999) values would considerably reduce the risks of triggering some nonlinear responses. In general, there is *low confidence* in the location of such temperature limits owing to disagreements among experts. Estimates of such temperature limits can change over time (Oppenheimer et al., 2008) and may be subject to overconfidence that can introduce a downward bias in risk estimates of low-probability events (Morgan and Henrion, 1990). The climate threshold responses can interact (e.g., Kriegler et al., 2009). Other climate change metrics (e.g., rates of changes or atmospheric CO_2 concentrations) can also be important in the consideration of response strategies aimed at reducing the risk of crossing thresholds (McAlpine et al., 2010; Lenton, 2011a).

Several analyses have performed risk- and decision-analyses for specific thresholds, mostly focusing on a persistent weakening or collapse of the AMOC (Zickfeld and Bruckner, 2008; Urban and Keller, 2010; Bahn et al., 2011; McInerney et al., 2012). Experiencing AMOC collapse has been assessed as *very unlikely* in this century and there is *low confidence* in assessing the AMOC beyond the 21st century (WGI AR5 SPM). However, owing to lags in the ocean system, the probability of triggering an eventual collapse differs from that of experiencing such an outcome (Urban and Keller, 2010). A probabilistic analysis sampling a subset of the relevant uncertainties concluded that reducing the probability of a collapse within the next few centuries to one in ten requires emissions reductions of roughly 60% relative to a business-as-usual strategy by 2050 (McInerney and Keller, 2008). Bruckner and Zickfeld (2009) show that, under their worst-case assumptions about key parameter values, emissions mitigation would need to begin within the next 2 decades to avoid reducing the overturning rate by more than 50%.

Threshold risk estimates and evaluations of risk-management strategies are sensitive to factors such as the representation of uncertainties and the decision-making frameworks used (Polasky et al., 2011; McInerney et al., 2012). Several analyses have examined how the consideration of threshold events affects response strategies. For example, the design of risk-management strategies could be informed by observation and projection systems that would provide an actionable early warning signal of an approaching threshold response. Learning about key uncertain parameters (e.g., climate sensitivity or impacts of a threshold response) can considerably affect risk-management strategies and have a sizable economic value of information (Keller et al., 2004; Lorenz et al., 2012). However, there is limited evidence about the feasibility and requirements for such systems owing to the small number of studies and their focus on highly simplified situations (Keller and McInerney, 2008; Lenton, 2011b; Lorenz et al., 2012). In some decision-analytic frameworks, knowing that a threshold has been crossed can lead to reductions in emissions mitigation and a shift of resources toward adaptation and/or geoengineering (Keller et al., 2004; Guillerminet and Tol, 2008; Swart and Marinova, 2010; Lenton, 2011b).

19.7.4. Avoiding Tipping Points in Social/Ecological Systems

Tipping points (see Glossary) in socio-ecological systems are defined as thresholds beyond which impacts increase nonlinearly to the detriment of both human and natural systems. These can be initiated rapidly, inducing a need for rapid response. For example, regime shifts have already occurred in marine food webs (Byrnes et al., 2007; Green et al., 2008; Alheit, 2009; Section 6.3.6) due to (observed) changes in sea surface temperature, changes in salinity, natural climate variability, and/or overfishing.

Because human and ecological systems are linked by the services that ecosystems provide to society (McLeod and Leslie, 2009; Lubchenco and Petes, 2010), tipping points may be crossed when either the ecosystem services are disrupted and/or social/economic networks are disrupted (Renaud et al., 2010). Climate change provides a stress that increases the risk that tipping points will be crossed, although they may be crossed due to other types of stresses even in the absence of climate change. For example, in dryland ecosystems, overgrazing has caused grassland-to-desert transitions (Pimm, 2009).

The likelihood of crossing tipping points due to climate change may be reduced by preserving ecosystem services through (1) limiting the level and rate of climate change (*medium confidence*) and/or (2) removing concomitant stresses such as overgrazing, fishing, habitat destruction, and pollution. Most literature currently focuses on strategy (2), and there is limited information about the exact levels and rates of climate change that specific coupled socioeconomic systems can withstand. Examples of strategy (2) include maintaining resilience of coral reefs and cephalopod or piscivorous seabird populations by removal of concomitant stress from fishing (Andre et al., 2010; Anthony et al., 2011; see also Sections 6.3.6, 30.6.2) or expanding protected area networks (Brodie et al., 2012). Removal of concomitant stress such as nutrient loading can reduce the chance of a regime shift (Jurgensone et al., 2011) in coral reef ecosystems (De'ath et al., 2012). Sometimes management can reverse the crossing of a tipping point, for example, by adding sediment to a submerged salt marsh (Stagg and Mendelssohn, 2010). Strategy (2) is enhanced by resilience-based management approaches in ecosystems (Walker and Salt, 2006; Lubchenco and Petes, 2010; Allen et al., 2011; Selig et al., 2012). A high level of biodiversity increases ecosystem resilience and can enable recovery after crossing a tipping point (Brierley and Kingsford, 2009; Lubchenco and Petes, 2010). Strategy (2) generally becomes ineffective once climate changes beyond an uncertain and spatially variable threshold; also successive thresholds may be crossed as stress increases (Renaud et al., 2010).

Monitoring that aims to detect a slowdown in the recovery of systems from small changes (van Nes and Scheffer, 2005) or to measure an appropriate indicator (Biggs et al., 2008) may give warning that a system is a approaching a regime shift, justifying intervention of type (2) (Guttal and Jayaprakash, 2009; Brock and Carpenter, 2010). Such indicators have been identified for the desertification process in the Mediterranean (Kéfi et al., 2007) and for landscape fire dynamics (Zinck et al., 2011; McKenzie and Kennedy, 2012).

19.7.5. Limits to Adaptation

Sections 16.2 and 16.4 provide a thorough assessment of the literature on limits to adaptation. Discussions are beginning on the nature of such limits, for example, in terms of different dimensions of the limits to adaptation, including financial or economic limits to adapt, but also social and political or cognitive limits of adaptation. Limits to adaptation (see, e.g., Adger et al., 2009) are also recognized in terms of specific geographies, for example, SIDS and their limited ability to adapt to increasing impacts of sea level rise, the limits to adaptation of urban agglomerations and urban dwellers in low-lying coastal zones (see, e.g., Birkmann et al., 2010), or in relation to loss of water supplies as a result of glacier retreat (Orlove, 2009). Overall, the concept of limits to adaptation is closely related to key vulnerabilities and key risks including those identified in Table 19-4 and Box CC-KR, because this concept helps define residual risk.

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Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development

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Executive Summary

Climate change calls for new approaches to sustainable development that take into account complex interactions between climate and social and ecological systems. Climate-resilient pathways are development trajectories that combine adaptation and mitigation to realize the goal of sustainable development. They can be seen as iterative, continually evolving processes for managing change within complex systems.

This chapter integrates a variety of complex concepts in assessing climate-resilient pathways. It takes sustainable development as the ultimate goal, and considers mitigation as a way to keep climate change moderate rather than extreme. Adaptation is considered a response strategy to anticipate and cope with impacts that cannot be (or are not) avoided under different scenarios of climate change. In most cases, sustainable development will also involve capacities for implementing and sustaining appropriate risk management. Responses may differ from situation to situation, calling for a multiscale perspective that takes the socioeconomic, cultural, biophysical, and institutional context into account. Nonetheless, most situations share at least one fundamental characteristic: threats to sustainable development are greater if climate change is substantial rather than moderate. Similarly, opportunities for sustainable development are greater if climate change is moderate rather than substantial.

Although findings from this chapter are based on a high level of consensus in source materials and in the expert communities, the amount of supporting evidence is relatively limited because so many aspects of sustainable development and climate change mitigation and adaptation have yet to be experienced and studied empirically. The task of this chapter is to suggest options to be considered for decision making, both now and in the future, as elements of the evolving processes for a variety of locations and scales. This chapter's findings are as follows.

Climate change poses a moderate threat to current sustainable development and a severe threat to future sustainable development (*high confidence*; *medium evidence*, *high agreement*). Some climate-related impacts on development are already being observed (e.g., changes in agriculture, increases in coastal vulnerability). Added to other stresses such as poverty, inequality, or diseases, the effects of climate change will make sustainable development objectives such as food and livelihood security, poverty reduction, health, and access to clean water more difficult to achieve for many locations, systems, and affected populations. {20.2.1}

Climate-resilient pathways include strategies, choices, and actions that reduce climate change and its impacts. They also include actions to ensure that effective risk management and adaptation can be implemented and sustained (*high confidence*; *medium evidence*, *high agreement*). Adaptation and mitigation have the potential to both contribute to and impede sustainable development, and sustainable development strategies and choices have the potential to both contribute to and impede climate change responses. Adaptation and mitigation are needed, working together to reduce risks of disruptions from climate change. These actions, however, may introduce trade-offs between adaptation and mitigation, and between economic goals and environmental goals. In some cases, for example, adaptation may increase greenhouse gas emissions (e.g., increased fossil-based air conditioning in response to higher temperatures) and in some cases mitigation may impede adaptation (e.g., reduced energy availability in countries with growing populations). In many cases, strategies for climate change responses and strategies for sustainable development are highly interactive. {20.3-4}

The integration of adaptation and mitigation responses can in some cases generate mutual benefits, as well as introduce co-benefits with development policies (*high confidence*; *medium evidence*, *medium agreement*). In many cases, reducing the risk of climate change can enhance capacities for management of other risks. Opportunities to take advantage of positive synergies may decrease with time, particularly if the limits to climate change adaptation are exceeded. {20.2.1, 20.3.2-3, 20.5.1}

Prospects for climate-resilient pathways are related fundamentally to what the world accomplishes with climate change mitigation, but both mitigation and adaptation are essential for climate change risk management at all scales (*high confidence*; *medium evidence*, *high agreement*). As the magnitude of climate change increases and the consequences become increasingly significant to many areas, systems, and populations, the challenges to sustainable development increase. Beyond some magnitudes and rates of climate change, the impacts on most systems would be great enough that sustainable development may no longer be possible for many systems and locations. At the local scale, governments, businesses, communities, and individuals in many developing regions have limited capacities to mitigate climate change because they contribute very little to global emissions. They may also have relatively limited capacities to adapt for reasons of income, education, health, security, political power, or access to technology. At all scales, however, mitigation and adaptation actions are fundamental for effective implementation of climate risk management and reduction. {20.2.2, 20.3, 20.6.1}

To promote sustainable development within the context of climate change, climate-resilient pathways may involve significant transformations (*high confidence*; *medium evidence*, *high agreement*). Transformations in economic, social, technological, and political decisions and actions can enable climate-resilient pathways. Although transformations may be reactive, forced, or induced by random factors, they may also be deliberately created through social and political processes. Whether in relation to mitigation, adaptation, or sustainable development, it is possible to identify enabling conditions that support transformations. Nonetheless there are legitimate concerns about the equity and ethical dimensions of transformation. {20.5}

Strategies and actions can be pursued now that will move toward climate-resilient pathways while at the same time helping to improve livelihoods, social and economic well-being, and responsible environmental management (*high confidence*; *medium evidence*, *high agreement*). Transformations to sustainability benefit from iterative learning, deliberative processes, and innovation. {20.4}

Delayed action in the present may reduce options for climate-resilient pathways in the future (*high confidence*; *medium evidence*, *high agreement*). In some parts of the world, current failures to address effects of emerging climate stressors are already eroding the basis for sustainable development and offsetting previous gains. Opportunities to design and implement solutions that promote climate-resilient pathways exist now, and they can capture development co-benefits of improving livelihoods and social and economic well-being. Current actions will emphasize climate risk management strategies informed by growing evidence, knowledge, and experience. {20.6.2}

More research about the relationship between mitigation, adaptation, and sustainable development is needed, as well as research on the relationship between incremental changes and more significant transformations for sustainable development (*high confidence*; *robust evidence*, *high agreement*). Priorities for research include improving understandings of benefits, costs, synergies, trade-offs, and limitations of major mitigation and adaptation options, along with implications for equitable development to facilitate decision making about climate-resilient pathways (*high confidence*; *robust evidence*, *high agreement*).

20.1. Introduction

Following summaries of *what we know* about climate change impacts, vulnerabilities, and prospects for adaptation (Chapter 18) and reasons for concern (Chapter 19), this chapter summarizes what is currently known about options regarding *what to do* in responding to these risks and concerns.

In terms of "what to do" to address climate change and threats to development now and in the future, the chapter identifies and discusses climate-resilient pathways. Climate-resilient pathways are defined in this chapter as development trajectories that combine adaptation and mitigation with effective institutions to realize the goal of sustainable development. They are seen as iterative, continually evolving processes for managing change within complex socio-ecological systems; taking necessary steps to reduce vulnerabilities to climate change impacts in the context of development needs and resources, building capacity to increase the options available for vulnerability reduction and coping with unexpected threats; monitoring the effectiveness of vulnerability reduction efforts; and revising risk reduction responses on the basis of continuous learning. As such, climate-resilient pathways include two main categories of responses:

- Actions to reduce human-induced climate change and its impacts, including both mitigation and adaptation toward achieving sustainable development
- Actions to ensure that effective institutions, strategies, and choices for risk management will be identified, implemented, and sustained as an integrated part of achieving sustainable development.

In many cases, each of the two categories of responses has the potential to benefit the other as well, offering potentials for win-win kinds of integration, although mechanisms and institutions are needed to address cases where the two elements have negative effects on each other and to ensure that positive synergies are realized. Because climate change challenges are significant for many areas, systems, and populations, climate-resilient pathways will generally require transformations—beyond incremental approaches—in order to ensure sustainable development (see Sections 20.2.3.1, 20.6.2; for related language employed by the UNFCCC, see Box 20-1).

Incremental responses to climate change address immediate and anticipated threats based on current practices, management approaches, or technical strategies. These may involve developing energy-efficient vehicles to mitigate climate change, or building higher dykes to adapt to sea level rise. Incremental responses are often referred to as business-as-usual approaches, as they do not challenge or disrupt existing systems (Kates et al., 2012). Transformative responses, in contrast, involve innovations that contribute to systemic changes by challenging some of the assumptions that underlie business-as-usual approaches (O'Brien, 2012). Transformational adaptations, for example, change the nature, composition, and/or location of threatened systems (Smit and Wandel, 2006; Stringer et al., 2009; National Research Council, 2010a; Pelling, 2010; IPCC, 2012). Importantly, transformations of the systems, structures, relations, and behaviors that contribute to climate change and social vulnerability may also be necessary to reduce risks to sustainable development, as discussed in Section 20.5.2 (see also WGIII AR5 Chapter 6 on Assessing Transformation Pathways).

Frequently Asked Questions

FAQ 20.1 | What is a climate-resilient pathway for development?

A climate-resilient pathway for development is a continuing process for managing changes in the climate and other driving forces affecting development, combining flexibility, innovativeness, and participative problem solving with effectiveness in mitigating and adapting to climate change. If effects of climate change are relatively severe, this process is likely to require considerations of transformational changes in threatened systems if development is to be sustained without major disruptions.

Conceptual understandings of sustainable development have developed considerably, particularly over the past 2 decades, as the short- and long-term implications of climate change and extreme events have become better understood, although empirical evidence of progress with sustainable development is often elusive. The discussion of sustainable development in the IPCC process has evolved since the First Assessment Report (FAR), which focused on the technology and cost-effectiveness of mitigation activities, and the Second Assessment Report (SAR), which included issues related to equity and to environmental and social considerations. The Third Assessment Report (TAR) further broadened the treatment of sustainable development by addressing issues related to global sustainability, and the Fourth Assessment (AR4) included chapters on sustainable development in both Working Group II and III reports, with a focus on both climate-first and development-first literatures.

This chapter recognizes climate change as a threat to sustainable development. The chapter emphasizes that, as a result, transformational changes are very likely to be required for climate-resilient pathways—both transformational adaptations and transformations of social processes that make such transformational adaptations feasible. The chapter integrates a variety of complex issues in assessing climate-resilient pathways in a variety of regions at a variety of scales: sustainable development as the ultimate aim, mitigation as the way to keep climate change impacts moderate rather than extreme, adaptation as a response strategy the way to keep climate change impacts moderate rather than extreme or to cope with impacts that cannot be (or are not) avoided, and development pathways as contexts that shape choices and actions. It stresses needs and opportunities to make progress toward climate-resilient pathways now, rather than postponing responses to an indefinite future.

The chapter is organized in six parts: climate change as a threat to sustainable development, by assessing links between sustainable development and climate change as well as defining climate-resilient pathways (Section 20.2); contributions to resilience through climate change responses (Section 20.3); contributions to resilience through

Box 20-1 | Goals for Climate-Resilient Pathways

Climate-resilient pathways are development trajectories of combined mitigation and adaptation to realize the goal of sustainable development that help avoid "dangerous anthropogenic interference with the climate system" as specified in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC).

Article 2 of the UNFCCC outlines its ultimate objective as the "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system* … in order to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner." Article 3.4 of the Convention recognizes that "*Parties have a right to and should promote sustainable development.*" A number of recent decisions by the Conference of the Parties (COP) to the UNFCCC has attempted to recognize the scientific view that the increase in global temperature should be below 2°C and encourage long-term cooperative action to combat climate change. The Decisions agreed in Cancun at COP-16 recognize "… *deep cuts in global greenhouse gas emissions are required according to science*, and as documented in the Fourth Assessment Report of the IPCC, with a view to reducing global greenhouse gas emissions so as to hold the increase in global average temperature below 2°C above preindustrial levels … consistent with science … [and] also recognizes the need to consider … strengthening the long-term global goal on the basis of the best available scientific knowledge." The preamble of the Cancun Decisions highlights the central importance of the link between climate change and employment and "*Realizes that addressing climate change requires a paradigm shift towards building a low-carbon society that offers substantial opportunities and ensures continued high growth and sustainable development, based on innovative technologies and more sustainable production and consumption and lifestyles, while ensuring a just transition of the workforce that creates decent work and quality jobs*" (UNFCCC, 2011, Decision 1/CP.16). The 2011 COP, in a decision known as the Durban Platform, increases the strength of the language in the Decision 1/CP.17 to conclude, "… *climate change represents an urgent and potentially irreversible threat to human societies and the planet* and thus requires to be urgently addressed … with a view to accelerating the reduction of global greenhouse gas emissions…." This decision was followed by the decisions adopted in Doha at the 18th Conference of the Parties that noted with grave concern the significant gap between the aggregate effect of Parties' mitigation pledges in terms of global annual emissions of greenhouse gases by 2020 and aggregate emission pathways consistent with having a likely chance of holding the increase in global average temperature below 2°C or 1.5°C above preindustrial levels. As such, the current UNFCCC negotiations have identified +2°C or 1.5°C as the desirable target upper limit,implicitly equating this with "dangerous" in Article 2.

sustainable development strategies and choices (Section 20.4); determinants of resilience in the face of serious threats (Section 20.5); challenges in moving toward climate-resilient pathways (Section 20.6); and priority gaps in knowledge (Section 20.7).

Several of the terms that are central to this chapter have been defined earlier in the WGII contribution to the Fifth Assessment Report, including climate, adaptation, and mitigation. In addition, by "resilient" we mean a system's ability to anticipate, reduce, accommodate, and recover from disruptions in a timely, efficient, and fair manner (IPCC, 2012). For literatures on "sustainable development," see Section 20.2. A summary definition is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (see Glossary). It achieves continuing improvements in human well-being and ensures a sustainable relationship with a physical environment that is already under stress, reconciling trade-offs among economic, environmental, and other social goals through institutional approaches that are equitable and participative in order themselves to be sustainable.

Frequently Asked Questions

FAQ 20.2 | What do you mean by "transformational changes"?

Transformational change is a fundamental change in a system, its nature, and/or its location that can occur in human institutions, technological and biological systems, and elsewhere. It most often happens in responding to significantly disruptive events or concerns about them. For climate-resilient pathways for development, transformations in social processes may be required to get voluntary social agreement to undertake transformational adaptations that avoid serious disruptions of sustainable development.

20.2. Climate Change as a Threat to Sustainable Development

Climate-resilient pathways bring together (1) sustainable development as the larger context for societies, regions, nations, and the global community with (2) climate change effects as threats to (and possibly opportunities for) sustainable development and (3) responses to reduce any effects that would undermine future development and even offset already achieved gains. Resilience is defined in this report as the ability of a social, ecological, or socio-ecological system and its components to anticipate, reduce, accommodate, or recover from the effects of a hazardous event or trend in a timely and efficient manner (see Glossary). Climate resilience refers to the outcomes of evolutionary processes of managing change in order to reduce disruptions and enhance opportunities. Considering alternative climate-resilient pathways cannot be separated from levels of climate change. Overall, most climate change scientists, decision makers, and stakeholders agree that (1) there is a level of climate change that is low enough that climate resilience for most systems could be achieved without enormous efforts and widespread transformational adaptation; (2) there is a level of climate change that is high enough that climate resilience cannot be expected to cope with severe impacts on most systems (e.g., Rockstrom et al., 2009); and (3) between those two levels the challenges to climate resilience grow as the level of climate change rises. Scientists do not, however, agree on what magnitude of climate change (e.g., average global warming) defines each of the two levels. Some experts support the view (Box 20-1 and Section 20.3.1) that any level above 2°C would mean impacts that are incompatible with sustainable development (Metz et al., 2002). The Summary for Policymakers of the WGII AR4 indicated that there is an approximate threshold between 2.5°C and 3°C of warming, above which impact concerns are severe but below which concerns are less severe (IPCC, 2007b, Figure SPM.2; see also Smith et al., 2009). Other scientists are unconvinced that system sensitivities to climate parameters such as temperature increase are understood well enough to support any specific warming threshold (e.g., National Research Council, 2010c), and some scientists and policymakers are unconvinced that adaptive management and adaptive response capacities are well enough understood to support determinations of limits to adaptation and resilience (Chapter 16). Most experts in all three groups, however, agree that prospects for climate-resilient development pathways are related fundamentally to what the world accomplishes with climate change mitigation (e.g., New et al., 2012).

20.2.1. Links between Sustainable Development and Climate Change

20.2.1.1. Objectives of Sustainable Development

Different actors have used the concept of sustainable development to pursue a variety of objectives in policy and practice worldwide, with the common denominator of delivering improved human well-being while sustaining environmental services (Sen, 1999; Morgan and Farsides, 2009; Von Bernard and Gorbaran, 2010). "Sustainable development" is a concept rooted in concerns about balance in the relationships between society and nature (e.g., Brown, 1981). The Brundtland Report (WCED, 1987, p. 43) defines the idea as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." It contains within it two key concepts of "needs": in particular the essential needs of the world's poorest, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs (Rao, 2000). It stresses that equitable economic development is key to addressing environmental problems both in developing and developed regions in ways that are sustainable for the long term (Halsnaes et al., 2008; Lafferty and Meadowcroft, 2010).

Historically, policy and science have subsequently influenced the development of the concept. Concerns about declining environmental quality, and increasing population growth, coupled with increasing rates of consumption (energy, natural resources, input-intensive living standards), motivated changes in some countries, related for example to:

- Water and air quality standards
- Management of hazardous materials
- Changes in regulation (although some literature says that current institutional controls and linkages are counterproductive (Barker, 2008; O'Hara, 2009; Scrieciu et al., 2013))
- Agricultural and industrial practices
- Water and solid waste management
- A movement toward greater efficiency in resource use including recycling
- An emphasis on energy efficiency, progressing toward renewable energy as an alternative to non-renewable fossil fuel resources (Frey and Linke, 2002).

In this context, global discourse and practice have helped to establish principles and aspirational plans. Examples include Agenda 21, which is a comprehensive plan of action adopted at the 1992 Earth Summit by more than 178 governments (Sitarz, 1994) and the 2012 "Rio+20" conference, which issued a statement urging countries to renew their commitment to sustainable development. Improved understandings of the short- and long-term implications of climate change and extreme events (IPCC FAR, SAR, TAR, AR4, *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX)) have influenced conceptualizations of sustainable development and related objectives such as poverty reduction, health, livelihood and food security, and other aspects of human welfare related to the idea of "climate-resilient development." These discussions occurred against an emerging understanding of "rights to development" (e.g., UNFCCC Article 2), juxtaposed with the lack of consensus about justifiable patterns of consumption and a recognition that development processes have altered global environmental systems, including climates (Crutzen and Stoermer, 2000; IPCC, 2007a, 2012; Oliver-Smith et al., 2012). However, in practice some national authorities interpret sustainable development as pursuing current economic development (Beg et al., 2002; Swart et al., 2003; Arndt et al., 2012; Yohe, 2012), as many countries aspire to carbon-intensive development models akin to the systems in place in most industrialized countries—from food production, trade, and transport to household consumption (Grist, 2008; Brown, 2011; Sanwal, 2012).

In contrast, to many observers, carbon-intensive development models in industrialized and developing countries appear broadly inconsistent with objectives such as poverty reduction, improving human health, and securing food and livelihoods associated with the idea of sustainable development (Ehrenfeld, 2008; Grist, 2008; Marston, 2012; see also Victor and Rosenbluth, 2007; Victor, 2008) and with efforts to define and establish "safe operating spaces" for humanity (Röckstrom et al., 2009; Preston et al., 2013). While diverse interpretations of the concept are used, the literature suggests that many indicators of human welfare are already being compromised to some degree and at different scales by climate-related stressors (see Section 20.2.1.2).

One way that sustainable development pathways can contribute to climate resilience is by pursuing consumption patterns that ensure social and economic development while reducing use of natural resources and maintaining ecosystem services. It is possible that the desired objectives of consumption might be met in ways that require fewer resources and produce fewer emissions (Kates, 2000b; see also Leiserowitz et al., 2005). Ideas about equity and values play a role in sustainable development and how policy makers perceive trade-offs in aims to improve human well-being. In many cases, growth in consumption that raises human well-being (such as food and health services), especially among populations with incomes rising from low levels, is a catalyst for economic and social development (Clark et al., 2008; Deaton, 2008). In contrast, for populations already at high consumption levels, increasing material consumption does not necessarily translate into higher well-being (Easterlin, 1974, 2001; Adger, 2010; see also WGIII AR5 Chapter 4). This observation is reflected in research on subjective human happiness, satisfaction, and material comfort (Huesemann, 2006; Dolan and White, 2007; Fleurbaey, 2009; Cafaro, 2010; DeLeire and Kalil, 2010).

Box 20-2 | Key Reasons for Concern about Climate Change Effects on Sustainable Development

Chapter 19 identifies a number of "Key Risks, Key Vulnerabilities, and Reasons for Concern" (see especially Section 19.6.3 and Table 19-4). Emergent risks from climate change related to sustainable development include losses of ecosystem services, challenges to land and water management, effects on human health, particular risks of severe harm and loss in certain vulnerable areas, increasing prices of food commodities on the global market, consequences for migration flows at particular times and places, increasing risks of flooding, risks of food insecurity, systemic risks to infrastructures from extreme events, loss of biodiversity, and risks for rural livelihoods. These risks differ according to the magnitude of climate change and both regional and socioeconomic differences in vulnerability. Some unique and threatened systems are at risk at current temperatures, with risks increasing at even relatively small increases in global mean temperature. Risks grow if the magnitude of warming increases.

20.2.1.2. Risks and Threats Posed by Climate Change, Interacting with Other Factors and Driving Forces

As the implications of climate change and their extent become better understood (Chapter 18) and as particular reasons for concern have begun to come into focus (Chapter 19), climate change has been increasingly seen as an issue for sustainable development—with the potential either to aid or impede its successful implementation (e.g., Halsnaes et al., 2008; Munasinghe, 2010).

The links between sustainable development and climate adaptation and mitigation are cross-cutting and complex. First, the impacts of climate change, and ill-designed responses to these impacts, may derail current sustainable development policy and potentially offset already achieved gains. These impacts are expected to affect numerous sectors such as agriculture, forestry, and energy; threaten coastal zones and other vulnerable areas; and pose critical challenges to governance and political systems (World Bank, 2010, pp. 39-69; Adger et al., 2011; IPCC, 2012; see also Box 20-2 and Chapters 18, 19). Examples include poverty and livelihoods (Chapter 13), food security (Chapter 7), human security (Chapter 12), rural and urban areas (Chapters 8, 9), and economic sectors (Chapters 10, 17). For instance, effects of climate change on key ecological resources and systems can jeopardize sustainable development in systems closely dependent on natural capital. Moreover, although impacts will affect both developed and developing regions, the latter are considered especially problematic owing to lower adaptive capacity (World Bank, 2010, Chapter 13; Lemos et al., 2013). Second, mitigation has the potential to keep these threats at a moderate rather than extreme level, and adaptation will enhance the ability of different systems to cope with the remaining impacts, therefore modulating negative effects on sustainable development (IPCC, 2007a).

Third, many of the conditions that define vulnerability to climate impacts and the ability to mitigate and adapt to them are firmly rooted in development processes (e.g., structural deficits and available assets and entitlements) (Brooks et al., 2005; Lemos et al., 2013; see also Section 15.2.1). Indeed, climate change will act as a threat multiplier and will create new poor in low-income countries and middle- to high-income countries (Chapter 13). Fourth, sustainable development intersects with many of the drivers of climate change, especially regarding energy production and consumption and the ability to mitigate emissions (IPCC, 2011; see also Chapter 9). Fifth, because several of the desirable characteristics of climate responses and sustainable development may overlap (e.g., implementation of no-regrets options, equitable distribution of resources, increased adaptive capacity and livelihood capitals, functioning ecosystems and maintained biodiversity), systems that prioritize sustainable development may be better at designing and implementing successful mitigation and adaptation (Forsyth, 2007; Brown, 2011).

Finally, climate mitigation and adaptation, if planned and integrated well, have the potential to create opportunities to foster sustainable development (see Section 20.3.3). Under the threat of climate change, sustainable development depends on changes in social awareness and values that lead to innovative actions and practices, including increased attention to both disaster risk management and climate change adaptation in anticipation of (and in response to) changes in climate extremes (IPCC, 2012). Understanding how to enhance positive feedbacks between mitigation, adaptation, and sustainable development (e.g., win-win and triple-win interventions) while minimizing potential trade-offs between them (see Section 20.3.3) is an essential part of planning for and pursuing climate-resilient pathways. In the following paragraphs, we discuss these links in light of empirical research and specific examples (Box 20-2; also see discussions of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) in Chapter 1). While some of the links described above have been contemplated in the scholarly literature, there remain considerable gaps in our knowledge base to inform climate-resilient pathways.

The relationship between climatic change and development policy has often been theorized as essentially twofold. On the one hand, climate change will affect development policy as needs to respond to negative, and perhaps positive, impacts arise (Burton et al., 2002; Halsnaes and Verhagen, 2007; IPCC, 2007a; Schipper, 2007). On the other hand, development policy critically shapes carbon emission paths, the ability to develop sustainable adaptation and mitigation options, and to build overall adaptive capacity (Bizikova et al., 2007; Metz and Kok, 2008; Garg et al., 2009; Lemos et al., 2013). Because of the recognized relationship between development and climate change drivers and responses, some authors have called for a "political economy of climate change" that takes into consideration ideas, power, and resources at different scales from the local to the global (e.g., Tanner and Allouche, 2011).

Enhancing resilience to respond to effects of climate change includes adopting good development practices that are consonant with building sustainable livelihoods and, in some cases, challenging current models of development (Boyd et al., 2008; McSweeny and Coomes, 2011). Moreover, promoting development pathways that are both equitable and sustainable is also a key to addressing climate change (Wilbanks, 2003; Nelson et al., 2007). In this sense, integrating sustainable development and overall climate change policy can be all the more relevant if "cross-linkages between poverty, the use of natural capital and environmental degradation" are recognized (Veeman and Politylo, 2003, p. 317; see also Matthew and Hammill, 2009). Especially in less developed regions, the relationship between vulnerability to climate impacts and development is often very close and mutually dependent, as such realities as low per capita income and inequitable distribution of resources; lack of education, health care, and safety; and weak institutions and unequal power relations fundamentally shape sensitivity, exposure, and adaptive capacity to climate impact (Kates, 2000a; Adger et al., 2003; Garg et al., 2009; McSweeny and Coomes, 2011; Lemos et al., 2013). In these regions, reducing risks that affect resource-dependent communities is increasingly viewed as a necessary but insufficient way to tackle the myriad problems associated with climate change impacts (Jerneck and Olsson, 2008). Building the capacity of individuals, communities, and governance systems to adapt to climate impacts is both a function of dealing with developmental deficits (e.g., poverty alleviation, reducing risks related to famine and food insecurity, enabling/implementing public health and mass education and literacy programs) and of improving risk management (e.g., alert systems, disaster relief, crop insurance, seasonal climate forecasts, risk insurance) (Mirza, 2003; Schipper and Pelling, 2006; IPCC, 2012; Warner et al., 2012a; see also Chapters 12, 13). Hence, it is important to understand not only the relative importance of different kinds of interventions (climate and non-climate) in building adaptive capacity but also the potential positive and negative synergies between them (Lemos et al., 2013).

Frequently Asked Questions

FAQ 20.3 | Why are climate-resilient pathways needed for sustainable development?

Sustainable development requires managing many threats and risks, including climate change. Because climate change is a growing threat to development, sustainability will be more difficult to achieve for many locations, systems, and populations unless development pathways are pursued that are resilient to effects of climate change.

While research increasingly highlights the intersection between vulnerability, adaptive capacity, and developmental structural deficits (see Chapter 13 for a detailed discussion), there is also growing recognition that the intractability of many of these problems may inhibit the development of climate-resilient pathways. For example, in northeast Brazil, the fact that local traditional politics relied on patron-client relationships with drought-affected households to maintain power suggests that there was little incentive for policies that dramatically decreased their level of vulnerability (Tompkins et al., 2008). Omolo (2010) argues that in northwestern Kenya, in pastoralist societies of Turkana, in spite of increasing numbers of women-headed households, participation of women in key decisions such as investment, resource allocation, and planning on where to move or settle in the aftermath of drought and floods is still quite low. A serious concern is that our inability to readily address these kinds of structural problems may limit options for future generations of marginalized social groups to be active agents of a climate-resilient future. In this sense, it is critical to understand how existing path-dependent trajectories (e.g., socio-technical, behavioral, institutional) that form the contextual basis for climate change action at different scales (Burch, 2010) may inhibit (or help) the realization of future climate-resilient pathways.

A number of studies recognize that not every possible response to climate change is consistent with sustainable development, as some strategies and actions may have negative impacts on the well-being of others and of future generations (Gardiner et al., 2010; Eriksen et al., 2011; see also Section 19.3.2.5). For example, some mitigation interventions such as the subsidization of the ethanol industry in the USA might compromise long-term resilience through both undesirable ecological effects (e.g., loss of crop diversity, soil erosion, and aquifer depletion) and social effects (e.g., reduction of flexibility for alternative fuel development, potential for food insecurity; Adger et al., 2011). Likewise, in central Vietnam some responses to climate change impact, such as building dams to prevent flooding and saltwater intrusion and to generate power, threaten the livelihood of poor communities. First, the relocation of communities and the inundation of forestland to build dams limit households' access to land and forest products. Second, a government focus on irrigated rice agriculture can reduce poor households' ability to diversify their income portfolio, decreasing their long-term adaptive capacity (Beckman, 2011). Indeed, the consequences of responses to climate change, whether related to mitigation or adaptation, can negatively influence future vulnerability, unless there is awareness of and response to these interactions (Eriksen et al., 2011). Here, the role of values in responding to climate change becomes important from a variety of perspectives, including intergenerational, particularly when those currently in positions of power and authority assume that their prioritized values will be shared by future generations (O'Brien, 2009; Eriksen et al., 2011). Acknowledging the importance of intergenerational equity, it has been argued that participatory processes and "deliberative democracy" can include the concerns, values, and perceptions of a wide range of stakeholders, raising some of the ethical impacts attached to climate-related risks (Backstrand, 2003; see also Deere-Birebeck, 2009). Such an approach could have a bearing on the way risks are assessed and addressed at the science-policy interface, with significant implications for sustainable development. For example, research by Wolf et al. (2009) on climate change responses in western Canada shows that individual quests to minimize their environmental impact and sense of responsibility (normatively defined as ecological citizenship) play an important role in the identification and implementation of sustainable responses to water scarcity. In contrast, inequitable distribution of power among those affected by climate impact can suppress innovative decisions about the future by limiting participation in designing solutions. In light of the complex interactions among climate change responses and sustainable development, there is a need for more holistic responses that place human well-being and security at the forefront, while building on existing strengths and capacities (Tompkins and Adger, 2004; O'Brien et al., 2010). This entails integrating multiple objectives and policy goals in order to promote responses to climate change that contribute to resilience and that are sustainable as social and policy conditions change (Meadowcroft, 2000; Tompkins and Adger, 2004; Pintér et al., 2011).

A reality in many countries may be that development in its many forms (economic, human, and sustainable) can enhance the capacity to adapt (Lemos et al., 2013), while at the same time adding to greenhouse gas (GHG) emissions. Yet, the World Development Report 2010 suggests that climate change responses have the potential to contribute to sustainable development as, for example, in the case of financial assistance with transition to low-carbon growth paths (World Bank, 2010) or in the case of mitigation policies that could increase income and/or enhance the quality of growth in vulnerable groups such as Reducing Emissions from Deforestation and Forest Degradation in Developing Countries (REDD+). And while vulnerable sectors such as agriculture give us particular reasons for concern (see Box 20-2), they may offer opportunities in some instances to reduce climate-related risks and threats by integrating both adaptation and mitigation strategies as a lever for reducing poverty and promoting climate-resilient pathways. Particularly necessary is addressing institutional and social capacities for responding to both climate change impacts and mitigation responses. For example, Chhatre and Agrawal (2009) show that climate change mitigation can benefit livelihoods if ownership of forest commons is transferred to local communities.

Some interventions related to climate change responses aim to combine goals of sustainable development, climate change adaptation, and climate change mitigation into "win-win" or "triple-win" approaches that highlight overlaps between these goals. Examples include mechanisms such as the Clean Development Mechanism (CDM) and Joint Implementation (JI) (e.g., Millar et al., 2007), which may seek to offset carbon emissions, build adaptive capacities of local communities, and provide sustainable development dividends despite mixed results in terms of accomplishing these goals in practice (Corbera and Brown, 2008). Specifically in the case of the CDM, robust empirical research shows overwhelming negative results in win-win terms—while the goal of offsetting carbon emissions has fared better, generating sustainable development dividend has been difficult. For example, after examining 16 existing CDM projects around the world, Sutter and Parreno (2007) found that whereas they could meet 72% of their emissions reduction goals, fewer than 1% might actually contribute significantly to sustainable development in the host country. Furthermore, their research suggests that there might be an actual trade-off between the goals of efficient generation of certified emissions reduction (CERs) and the broader generation of the sustainable development dividend (see also Winkelman and Moore, 2011). Even when relatively successful, triple-win interventions may result in unequal distribution of benefits across mitigation, adaptation, and sustainable development (Bryan et al., 2013). Because relationships among the three goals can lead to both positive and negative consequences, it is important to unravel conditions that lead to desirable outcomes (Chhartre and Agrawal, 2009) (see Section 20.3.3). Moreover, the fact that currently available institutional arrangements that attempt to combine mitigation and sustainable development (such as CDM) are not achieving win-win goals indicates the need for rapidly developing means for evaluating, changing, and improving current policy instruments and mechanisms (Dovers and Hezri, 2010).

Given these connections, there is growing consensus in the literature about a need to integrate development and climate policies; however, the means to achieve this integration differ and are not without controversy (see, e.g., Seballos and Kreft, 2011). An approach often described in the literature is mainstreaming, where governments incorporate climate-related concerns into existing policy (Dovers and Hezri, 2010). A major factor constraining the "mainstreaming" of climate adaptation into development is the disconnect between access to globally available adaptation funds and developing countries' own development agendas (Hardee and Mutunga, 2009; Seballos and Kreft, 2011). This disconnect can potentially inhibit the development of robust local organizations and institutions that effectively integrate or mainstream climate change considerations into development priorities. In particular, research focusing on the National Adaptation Programmes of Action (NAPAs) and the Strategic Programmes for Climate Resilience (SPCRs), designed to support least developed countries to mainstream adaptation, shows that lack of coordination between government sectors, lack of technical capacity, and discrepancies between long-term development goals and short-term adaptation interventions still constrain mainstreaming efforts (Saito, 2013; see also Section 15.2). Even where climate-related initiatives and programs are reasonably well coordinated, bureaucratic complexities can cause communities to be overlooked (Chukwumerije and Schroeder, 2009). For example, in Mexico, despite the governmental discourse supporting climate change policy, actual implementation of mitigation and adaptation actions have been constrained by lack of resources and institutional coordination and limited societal involvement (Sosa-Rodriguez, 2013). Other factors—such as lack of financial and human resources, unclear distribution of costs and benefits, fragmented management, mismatches in scale of governance and implementation, lack and unequal distribution of climate information, lack of institutional memory, and trade-offs with other priorities—may also limit the smooth mainstreaming of climate adaptation action into development (Eakin and Lemos, 2006; Bizikova et al., 2007; Agrawala and van Aalst, 2008; Kok et al., 2008; Metz and Kok, 2008, Sietz et al., 2011). Finally, empirical evidence suggests that the relationship between development variables and climate change responses can be a mixture of positives and negatives, if development variables are not managed well (Garg et al., 2009). For example, in a study of the relationship between malaria incidence, development, and climate variables in India, Garg et al. (2009) found that while some development interventions such as building irrigation canals and dams can, in some cases, increase the incidence of malaria and water-borne diseases (when they exacerbate potential breeding grounds for malarial parasites), others such as higher per capita income can reduce negative health impacts of climate change significantly—although the distribution of benefits can differ between types of interventions (also see Campbell-Landrum and Woodruff, 2006). Understanding how development variables intersect with climate responses is especially important because governments and other actors rarely make decisions in isolation; rather, they respond to multiple stressors both in rural and urban environments (Eakin, 2005; Agrawal, 2010; Wilbanks and Kates, 2010; Lemos et al., 2013). Moreover, some evidence suggests that, in practice, decision makers (from heads of households to policy makers) often do not place climate change at the top of their priority list of critical issues to address (Garg et al., 2007; Kok et al., 2008), although this situation seems to be changing. Moreover, the increasing importance of climatic change in shaping social and governmental policy agendas has resulted in a growing number of examples of specific interventions to respond to climate change, both in developed and developing regions (Ayers and Huq, 2009; Burch, 2010; Bierbaum et al., 2013; for examples of adaptation planning see Chapter 15, especially Section 15.2, and Chapter 14, especially Section 14.3).

20.2.2. Climate-Resilient Pathways

20.2.2.1. Framing Climate-Resilient Pathways

Climate-resilient pathways integrate current and evolving understandings of climate change consequences and conventional and alternative development pathways to meet the goals of sustainable development (see WGIII AR5 Chapter 4). They can be seen as development trajectories that include both mitigation and adaptation, as well as effective development institutions. Climate-resilient pathways represent iterative processes for managing change within complex systems, where unintended consequences are common owing to feedbacks, teleconnections, cross-scale linkages, thresholds, and nonlinear effects (Folke et al., 2002; Scheffer et al., 2009; Lenton, 2011a). Climate-resilient pathways recognize that increasing atmospheric concentrations of GHGs can lead to impacts that have long-term implications for sustainable development. The observed and projected impacts of climate change on poverty and livelihoods, food and water security, health, and human security are well documented in this report (see Chapters 11, 12, 13).

The pursuit of climate-resilient pathways involves identifying vulnerabilities to climate change impacts; assessing opportunities for reducing risks; and taking actions that are consistent with the goals of sustainable development. These actions may involve a combination of incremental and transformative responses that take into account (1) current and anticipated changes in both climate averages and extremes; (2) the dynamic development context that influences social vulnerability, risk perception, conflict resolution, and resilience; and (3) recognition of human agency and capacity to influence the future. This last point is significant, as humans have the capacity to manage risk and to decrease vulnerability through both mitigation and adaptation, as well as through choices of development goals and strategies (IPCC, 2012).

Climate-resilient pathways call for decisions and actions that take into account both short- and long-term time horizons. In the short term, society will have to adapt to changes in the climate that are linked to past emissions, and both incremental and transformative adaptation may thus be significant. Mitigation responses taken in the short term will have a strong influence on climate-resilient pathways for sustainable development in the future, shaping needs for transformative adaptation over a long time horizon. Considering the potential for nonlinear impacts associated with increasing global temperatures, the threats to sustainable development are likely to become greater over time (Wilbanks et al., 2007; Stafford et al., 2010; see also Chapter 12). Discussions of climate-resilient pathways thus cannot be separated from levels of climate change.

20.2.2.2. Elements of Climate-Resilient Pathways

If climate change continues on its current path toward relatively significant impacts (National Research Council, 2010b), climate-resilient pathways will become increasingly challenging, requiring explicit attention to responses in virtually all regions, sectors, and systems to avoid disruptions of development processes. Climate-resilient pathways include two overarching attributes: (1) actions to reduce climate change and its impacts, including both mitigation and adaptation, and (2) actions to ensure that effective risk management institutions, strategies, and choices can be identified, implemented, and sustained as an integrated part of development processes (Edenhofer et al., 2012). Box 20-3 draws on material throughout the chapter to list a number of attributes of climate-resilient pathways categorized into awareness and capacity, resources, and practices. Each of the items is amenable to strategy development in appropriate national, regional, and local contexts. For example, in many cases effective response to extreme events can benefit both from iterative problem-solving and bottom-up engagement in risk management, and from human development to enhance capacities for risk management and adaptive behavior (Tompkins et al., 2008). Folke (2006) characterizes resilience as a process of innovation and development. Pathways should therefore be continuously moving toward a more adapted and less vulnerable state; in some instances,

Box 20-3 | Selected Elements of Climate-Resilient Pathways

Awareness and capacity

- A high level of social awareness of climate change risks
- A demonstrated commitment to contribute appropriately to reducing net greenhouse gas emissions, integrated with national development strategies
- Institutional change for more effective resource management through collective action
- Human capital development to improve risk management and adaptive capacities
- Leadership for sustainability that effectively responds to complex challenges

Resources

- Access to scientific and technological expertise and options for problem solving, including effective mechanisms for providing climate information, services, and standards
- Access to financing for appropriate climate change response strategies and actions
- Information linkages in order to learn from experiences of others with mitigation and adaptation

Practices

- Continuing development and evaluation of institutionalized vulnerability assessments and risk management strategy development, and refinement based on emerging information and experience
- Monitoring of emerging climate change impacts and contingency planning for responding to them, including possible needs for transformational responses
- Policy, regulatory, and legal frameworks that encourage and support distributed voluntary actions for climate change risk management
- Effective programs to assist the most vulnerable populations and systems in coping with impacts of climate change

there may be stages of slow development followed by periods where progress increases speed. Further, the nonlinearity, variability, and uncertainty of climate impacts necessitate a system that allows for the flexibility to adapt to unexpected and even extreme events (Holling, 1973). This is especially true in light of political, economic, or resource constraints, where pathways at the local level will need to be not only flexible but also practical and feasible in both the short term and long term. One of the most challenging aspects of climate-resilient pathways is that they exist in distinctive local contexts, where they are shaped by external linkages that connect them across geographic scales and time. For example, resilience cannot be achieved in a few privileged places if it is not achieved in other connected places, because instabilities in adversely impacted situations will spill over to other situations through such effects as resource supply constraints, conflict, migration, or disease transmission (Wilbanks, 2009; IPCC, 2012, Chapter 7).

Climate-resilient pathways are in fact a process, not an outcome (Manyena, 2006), involving both incremental and transformational changes. The pathways therefore need to be built on a foundation of constantly advancing knowledge, where information is adjusted based on changing scientific knowledge on climate parameters and altering social, economic, and natural resource situations (Berkes, 2007). While some measures will be reactive, the main elements of a pathway are intentional and proactive: anticipating future change and developing appropriate plans and responses. Although payoffs from specific long-term pathways may be unknown, strategies and actions can be pursued now that will contribute significantly to moving toward climate-resilient pathways while helping improve human livelihoods, social and economic well-being, and responsible environmental management (Section 20.6.2).

20.3. Contributions to Resilience through Climate Change Responses

Climate change responses include mitigation, adaptation, and integrated mitigation and adaptation strategies. Related to these responses but generally considered a separate response issue is "geoengineering" (see Box 20-4).

20.3.1. Mitigation

In IPCC's assessment reports, mitigation is the subject of WGIII, to which readers are referred for comprehensive information about options and strategies for reducing GHG emissions and increasing GHG uptakes by the Earth system. For this chapter, the issue is how climate change

Box 20-4 | Considering Geoengineering Responses

If climate change mitigation is not sufficiently successful, policymakers may be faced with demands to find further ways to reduce climate change and its effects.

Such options include intentional large-scale interventions in the Earth system either to reduce the amount of absorbed solar energy in the climate system or to increase the uptake of carbon dioxide (CO_2) from the atmosphere (see Glossary). An example of the former is to inject sulfates into the stratosphere. Examples of the latter include facilities to scrub CO_2 from the air and chemical interventions to increase uptakes by oceans, soil, or biomass (UK Royal Society, 2009; WGIII AR5 Chapter 6; WGI AR5 Chapters 6, 7; see also Chapter 19).

Discussions of geoengineering have only recently become an active area of discourse in science, despite a longer history of efforts to modify climate (Schneider, 1996, 2008; Keith, 2000; Crutzen, 2006). Many of the possible options are known to be technically feasible, but their costs, effectiveness, and side effects are exceedingly poorly understood (National Research Council, 2010b; Goes et al., 2011; MacCracken, 2011; Vaughan and Lenten, 2011). For example, some interventions in the atmosphere might not be unacceptably expensive in terms of direct costs, but they might affect the behavior of such Earth system processes as the Asian monsoons (Robock et al., 2008; Brovkin et al., 2009). Some interventions to increase carbon uptakes, such as scrubbing CO_2 from the Earth's atmosphere, might be socially acceptable but economically very expensive. Moreover, it is possible that optimism about geoengineering options might invite complacency regarding mitigation efforts.

In any case, implications for sustainable development are largely unknown. Even though some views have been expressed that geoengineering is needed now to avoid irreversible impact such as the loss of biodiversity (while many governments have not begun to consider it at all), several countries consider it a research priority rather than a current decision-making option (National Research Council, 2010b). The challenge is to understand what geoengineering options would do to moderate global climate change and also to understand what their ancillary effects and risks might be. This would allow policymakers in the future to respond if severe disruptions appear and, as a result, there is a need to consider rather dramatic technology alternatives. Some observers propose that research efforts should include limited experiments with geoengineering options, but agreement has not been reached about criteria for determining what experiments are appropriate or ethical (Chapter 19.5.4; WGIII AR5 Chapter 3.3.7; Blackstock and Long, 2010; Gardiner, 2010).

mitigation relates to sustainable development, which was addressed by WGII AR4 Chapter 12 (IPCC, 2007a) and is also the focus of WGIII AR5 Chapter 4, including attention to equity issues.

In general terms, mitigation is recognized to be important for sustainable development in two ways (Riahi, 2000). First, it reduces the rate and magnitude of climate change, which reduces climate-related stresses on sustainable development, including effects of extreme weather and climate events (Washington et al., 2009; Lenton, 2011b; IPCC, 2012; see also Section 20.2; Box 20-1). But recent observations of the rate of increase in global carbon dioxide emissions (e.g., Peters et al., 2013) suggest that the challenge of stabilizing concentrations is growing (for further information about international accords, national pledges and inventory reports, and continuing negotiations, along with summaries of current and projected progress with mitigation, see WGIII AR5).

Second, trajectories for technological and institutional change to reduce net GHG emissions interact with development pathways. In some cases, national pledges to achieve mitigation targets (e.g., Figure 20-1) may be congruent with sustainable development in urban settings, such as green growth strategies that reduce local and regional air pollution, enhancing prospects for multilevel governance and integrated management of resources, and encouraging broader participation in development processes (Lebel, 2005; Seto et al., 2010). In other cases, such effects as higher energy prices associated with transitions from fossil fuels to renewable energy sources have the potential to have adverse effects on local and regional economic and social development (IPCC, 2011, Chapter 9).

The challenge for climate-resilient pathways is to identify and implement mixes of technological and governance options that reduce net carbon emissions and at the same time support sustainable economic and social growth in a context where rising demands for economic and social development need to be combined with technology transitions without disrupting the development process. For example, strategies such as increasing carbon uptakes and decreasing carbon losses in the soil through better agricultural management practices—which can reduce net emissions—can improve soil water storage capacity. Practices such as conservation tillage can also increase water retention in drought conditions and help to sequester carbon in soils (Halsnaes et al., 2008). In many cases, however, this challenge remains very difficult to meet.

Mitigation and development also interact in a third way in that different groups and countries' abilities to implement mitigation critically depends on their "mitigative capacity" (Yohe, 2001): their "ability to reduce anthropogenic greenhouse gas emissions or enhance natural sinks" and the "skills, competencies, fitness, and proficiencies that a country has attained which can contribute to GHG emissions mitigation" (Winkler et al., 2007). Here, many of the determinants of mitigative capacity are fundamentally shaped by different countries' levels of development, including their current level of emissions; their stock of human, financial, and technological capital, such as the ability to pay for mitigation; the magnitude and cost of available abatement opportunities; the regulatory effectiveness and market rules; the education and skills base; the suite of mitigation technologies available; the ability to absorb new technologies; and the level of infrastructure development (Box 20-4).

20.3.2. Adaptation

Adaptation is the subject of four chapters of this WGII AR5 (Chapters 14 to 17), to which readers are referred for comprehensive descriptions of concepts, options, strategies, and examples of adaptation practices. For this section, we focus on the intersection between adaptation and sustainable development. Overall, climate adaptation and sustainable development are linked in several ways: first, many of the determinants of adaptive capacity to respond to climate impact and indicators of sustainable development overlap; second, adaptive capacity building may critically contribute to the well-being of both social and ecological systems; and third, building adaptive capacity within a sustainable development framework may require transformational changes (Dovers and Hezri, 2010; Kates et al., 2012; Lemos et al., 2013).

Around the globe, the ability of communities and individuals to respond to climate change is predicated on a number of capacities (e.g., human capital, information and technology, material resources and infrastructure, organizational and social capital, political capital, wealth and financial capital, institutions and entitlements) that typically overlap with indicators of development (Smit and Pilifozofa, 2001; Yohe and Tol, 2002; Eakin and Lemos, 2006). However, building these capacities both in developed and less developed regions has implications for sustainable development because it might increase the consumption of materials and create potential negative effects on ecosystems (e.g., building of new infrastructure and increasing consumption). In terms of governance, climate change adaptation and sustainable development share many characteristics (e.g., issues of spatial and temporal scales, uncertainty, poorly defined jurisdictions; Dovers and Hezri, 2010), and designing and implementing successful interventions require different kinds of capacities, including political and administrative structures (Eakin and Lemos, 2006; Wilbanks et al., 2007). Building adaptive capacity may critically contribute to the improvement of the well-being of both social and ecological systems by bettering livelihoods and reducing pressure

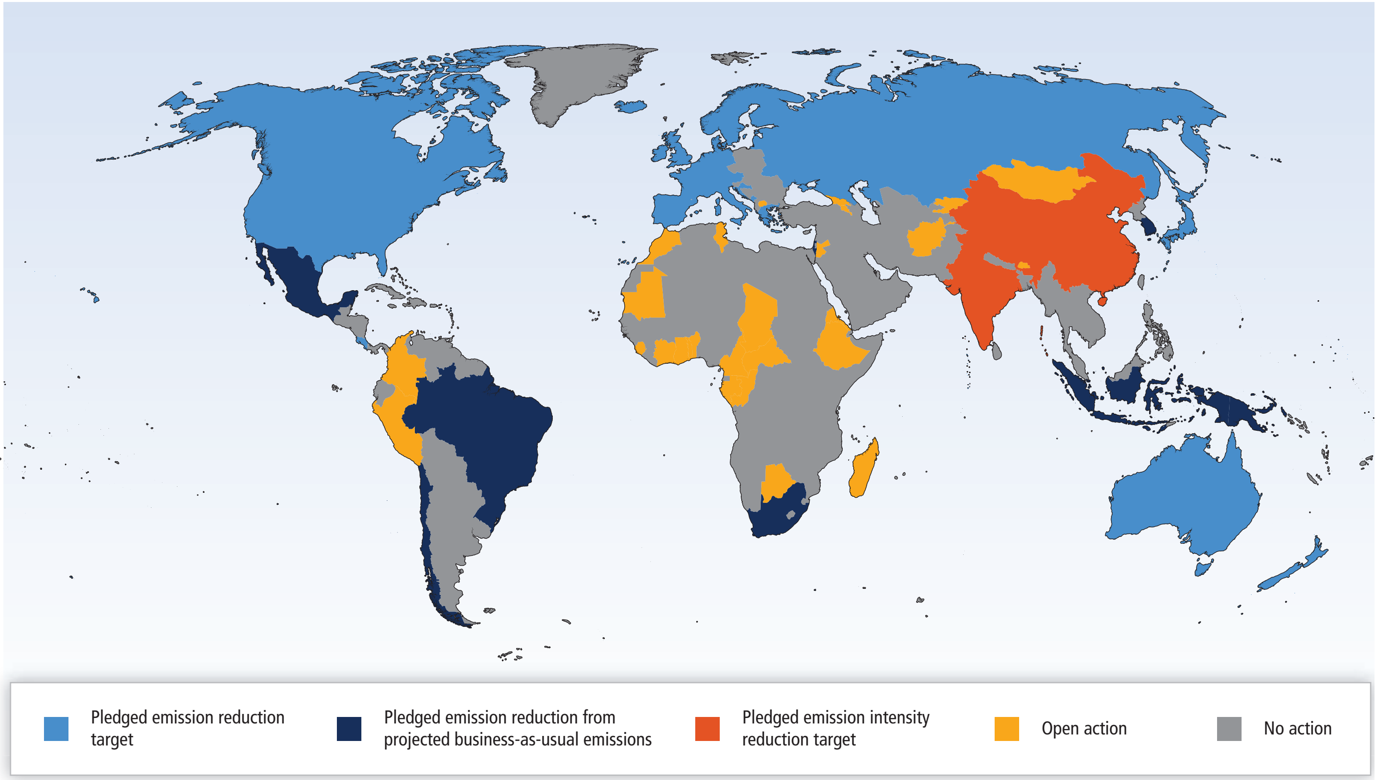

Figure 20-1 | Pledges by Annex 1 and Annex 2 countries in response to the Copenhagen Accord (see http://unfccc.int/meetings/copenhagen_dec_2009/items/5264.php, http://unfccc.int/meetings/cop_15/copenhagen_accord/items5265.php). Refer to Table SM21-1 for groupings of countries and territories of the world of relevance for international climate change policy making.

Box 20-5 | Case Studies from China

Water-saving irrigation has enhanced climate change adaptation capacity, improved ecosystem services, and promoted regional sustainable development in China:

- *Water-saving irrigation measures in cropland adaptation to climate change*. Water-saving irrigation is one effective measure to deal with the water scarcity and food security issues caused by climate change (Hanjra and Qureshi, 2010; Tejero et al., 2011). Given an increase in non-agricultural water consumption, China's agriculture could be faced with a severe shortage of water resources (Xiong et al., 2010). Through water-saving irrigation practices, water saved from 2007 to 2009 added up to a total of 61.82–129.66 10^9 m^3, which accounted for 5.6–11.8% of the national total water consumption; total energy saved was equal to 9.59–20.85 Mt of standard coal; and total CO_2 emissions were reduced by 21.83–47.48 Mt of CO_2. Therefore, water saving irrigation has had a positive effect in dealing with climate change and sustainable development (Zou et al., 2012).

Table 20-1 | Water and energy savings and CO_2 emission reductions from water-saving irrigation measures in cropland.

	2007	2008	2009
Water saved (10^9 m^3)	19.37–40.86	19.86–41.55	22.58–47.25
Energy saved (Mt of standard coal)	2.92–6.39	3.08–6.72	3.58–7.73
CO_2 emission reduction (Mt of CO_2)	6.66–14.58	7.02–15.31	8.15–17.59

- *Water-saving irrigation measures in alpine grassland for adapting to climate change*. In recent years, the rise in precipitation and temperature has led to the melting of glaciers and expansion to inland high mountain lakes, contributing to alpine grassland degradation in northern Tibet (Gao et al., 2010). Among many grassland protection measures, alpine grassland water-saving irrigation measures could be effective in redistributing and making full use of increased precipitation and lake water in the dry period, which would reduce the negative effects of climate change and make full use of favorable conditions (Editorial Board of National Climate Change Assessment, 2011; Gao et al., 2012). A 3-year demonstration of alpine grassland water-saving irrigation measures showed that alpine grassland primary productivity nearly doubled while the number of plant species increased from 19 to 29, helping to protect and restore the alpine grassland ecosystem and ecosystem services and to promote regional socioeconomic sustainable development in Northern Tibet (Gao et al., 2012).

on the environment, especially in less developed regions (see Section 20.4.3). Regarding social systems, it is important to consider not only the factors that enable the building of different capacities (e.g., institutions and governance) but also how to guarantee that those who need it the most have access to them (Nelson et al., 2007; Gupta et al., 2010). It is also vital to understand how different capacities influence each other, positively and negatively (Lemos et al., 2013), and how they may affect the long-term resilience of social-ecological systems (Adger et al., 2011; Box 20-5). Indeed, adaptation can be important in reducing stresses on development processes, especially in vulnerable areas where it can help to promote and support sustainable development. For example, where adaptation planning stimulates participatory social processes, including equity and legitimacy, as well as discussions regarding different adaptation options, it can encourage communities to think more clearly about broader sustainable development goals and pathways (National Research Council, 2010a).

Given recent trends in GHG emissions and projections of climate futures that suggest impacts of climate change will be serious and widespread (e.g., Auerswald et al., 2011; Smith et al., 2011), adaptation may require considering transformational changes, in which potentially impacted systems move to fundamentally new patterns, dynamics, and/or locations (Schipper, 2007; Kates et al., 2012; Marshall et al., 2012; Park et al., 2012). Desirable adaptation strategies may vary according to specific kinds of climate change threat, location, impacted system, the geographical scale of attention, and the time frame of strategic risk management planning (Thomalla et al., 2006; Heltberg et al., 2009; National Research Council, 2010a). Transformational adaptation policy at different scales needs to take into consideration the goals of sustainable development, both by fostering positive synergies and by avoiding negative feedbacks between them. This is especially important because some adaptation options might lead to inequitable and unsustainable outcomes, and some adaptations at one scale may negatively affect vulnerability in another (Thomas and Twyman, 2005; Eriksen et al., 2011; Eriksen and Brown, 2011; see also Sections 20.3.3, 20.4.4 and Chapter 14 for a more detailed discussion). For example, in the USA, building adaptive capacity for water management through drought preparedness plans at one scale (the state level) may constrain the flexibility of managers at lower scales (community water systems) to respond successfully to drought (Engle, 2013).

Indeed, adaptation pathways can foster food and water security, human health, and air and water quality and natural resource management, while promoting gender equality and other desirable outcomes consistent with sustainable development goals. However, creating the conditions for the emergence of such outcomes will require better integration in the implementation of policies and programs at all scales. By selecting materials not harmful to the environment, promoting the conservation of energy, water, and other resources, promoting reuse and recycling, minimizing waste generation, protecting habitat, and addressing needs of marginalized groups, adaptation can contribute to win-win and triple-win options that can support a diverse array of development goals (Bizikova et al., 2007; Seto et al., 2010; see also Sections 15.3.1, 20.3.3 and UNFCCC, 2011).

20.3.3. Integrating Climate Change Adaptation and Mitigation for Sustainable Risk Management

Because both adaptation and mitigation are parts of climate-resilient pathways, and because each benefits from progress with the other (e.g., Section 20.2), integrating the two kinds of climate change responses within the broader context of sustainable development has been suggested as an aspirational goal (Wilbanks et al., 2007; Bizikova et al., 2010), especially when policy attention and financial commitments to climate change responses must consider the pursuit of both adaptation and mitigation. In practice, however, mitigation and adaptation tend to involve different time frames, communities of interest, and decision-making responsibilities (IPCC, 2007a; Wilbanks et al., 2007).

Integration of climate change responses with development processes is a further aspirational goal. Recent research suggests that mitigation and adaptation are likely to be more effective when they are designed and implemented in the context of other interventions within the broader context of sustainability and resilience (Wilbanks and Kates, 2010; ADB and ADBI, 2012). Moreover, studies focusing on the intersection between sustainable development and climate policy point out that integration between the two is a desirable although complex path (Section 20.2.1.2; Beg et al., 2002; Robinson et al., 2006; Swart and Raes, 2007; Wilson and McDaniels, 2007; Halsnaes et al., 2008; Ayers and Huq, 2009). Wilson and McDaniels suggest three reasons to integrate across adaptation, mitigation, and sustainable development: (1) many dimensions of the *values* that are important for decision making are common to all three decision contexts; (2) impacts from any one of the three decision contexts may have important *consequences* for the others; and (3) the *choice among alternatives* in one context can be a means for achieving the underlying values important in the others.

A key factor in integrating climate change adaptation and mitigation into sustainable risk management is to understand the processes of decision making at different scales. The distribution of costs and benefits of mitigation and adaptation differ; for example, mitigation benefits are more global, adaptation benefits are often more localized, the research and policy discourses are often unrelated, and the constituencies and decision makers are often different (mitigation may involve powerful industrial stakeholders from the energy sector concentrated at higher levels of decision making, while adaptation may involve more dispersed stakeholders at the local level across sectors) (Wilbanks et al., 2007). To significantly reduce total global emissions, mitigation decisions must be taken either by major emitters, or by groups of countries. At the national and international level, direct responsibilities to curb the main drivers of global climate change are dispersed across countries (Banerjee, 2012). In contrast, adaptation often falls to practitioners where local responsibility is clearer, although it often depends on support from national and global scale (Tanner and Allouche, 2011).

In many cases, the challenge of fostering synergies while avoiding negative feedbacks often comes into focus in place-based discussions of climate change responses and development objectives such as localities and small regions (Dang et al., 2003; Wilbanks, 2003; Bulkeley and Schroeder, 2012). Globally, a particular hurdle is the practice of applying available mitigation resources only for reducing emissions beyond that which would have occurred without those resources ("*additionality*"), when access to resources for adaptation efforts should take into account the critical role of *co-benefits* in supporting development in other ways while at the same time reducing vulnerabilities to climate change impacts (National Research Council, 2010a; see also Section 20.4.1).

Choices in integrating adaptation and mitigation will vary according to the circumstances of each country and each locality (Wilbanks, 2003; De Boer et al., 2010). In highly vulnerable countries, adaptation may be seen as the highest priority because there are immediate benefits to be obtained by reducing vulnerabilities to current climate variability and extremes as well as future climate changes. In the case of developed countries, adaptation initiatives have often been seen as a lower priority because it is perceived that there is abundant adaptive capacity (Naess et al., 2005). Yet major losses and damages in some industrialized countries related to climatic variability and extremes challenge this perception (e.g., Hurricane Sandy, tornadoes, and drought in the USA in 2011 and 2012). Mitigation may be seen as more acute political question—involving well-organized stakeholders concerned about costs—in countries that contribute a large proportion of GHG emissions (e.g., National Research Council, 2011), and it may be seen as an investment opportunity for the domestic private sector.

As indicated above, one emerging strategy to integrate climate and development policies is the design of "win-win" and "triple-win" interventions that seek to achieve an appropriate mix of mitigation and adaptation within the context of sustainable development (Pyke et al., 2007; Swart and Raes, 2007). Swart and Raes suggest a number of factors that should be taken into consideration when evaluating combined adaptation and mitigation policy designs, including (1) avoiding trade-offs, when designing policies for mitigation or adaptation; (2) identifying synergies; (3) enhancing response capacity; (4) developing institutional links between adaptation and mitigation, for example, in national institutions and in international negotiations; and (5) mainstreaming adaptation and mitigation considerations into broader sustainable development policies. Box 20-5 provides a case study of an initiative in China that has been a winner for both climate change responses and regional sustainable development. The potential for climate-resilient pathways may already be limited, however, in part because of path dependency stemming from choices on mitigation, adaptation, and political interpretations and subsequent choices around "sustainable" development (Swart et al., 2003; Barker, 2008); and, in many cases, interventions have not delivered win-win results, which raises questions about the actual attainability of win-win strategies given legal, political, economic, and/or institutional obstacles (Warner et al., 2012b; see also Section 20.2.1.2).

In synthesizing evidence from a series of empirical articles focusing on the intersection between mitigation and adaptation (M&A), Wilbanks and Sathaye (2007) argue that M&A pathways might be alternatives in reducing costs, complementary to and reinforcing each other (e.g., improvements in building energy efficiency), or competitive and mutually contradictory (e.g., coastal protection vs. reductions in sea level rise). In Bangladesh, for example, waste-to-compost projects contribute to mitigation through reducing methane emissions; to adaptation through soil improvement in drought-prone areas; and to sustainable development through the preservation of ecosystem services (Ayers and Huq, 2009; also see Vergara et al., 2012, regarding possible development benefits of mitigation and adaptation in Latin America and the Caribbean). Land management and forestry activities contribute to ecosystem-based mitigation, for example, through the reduction of emissions from deforestation and forest degradation, and adaptation, for example, through the conservation of hydrological services provided to people facing water problems, as well as renewable energy (see several cases of ecosystem-based adaptation in Pramova et al., 2012). However, trade-offs are also possible, for example, if ecosystem management for mitigation purposes reduces the livelihood opportunities and the adaptive capacity of local people (Locatelli et al., 2011). The scale of these examples is often local, however, and longer term success of these pathways will depend on the broader context of mitigation and facilitation of adaptation options (Metz et al., 2002).

When integrating across the goal of finding climate-resilient pathways (and win-win solutions), decision makers often need to address issues of scale, along with trade-offs in values such as economic profitability versus stability of food and livelihood security (e.g., in agricultural policy), relationships between development ends and means, uncertainty and path dependencies, and institutional complexity (Tol, 2004; Klein et al., 2005; Wilson and McDaniels, 2007). They also need to consider the possibility of ancillary co-benefits, complementarities and potential contradictions, opportunity costs, and unknown negative and positive feedbacks (e.g., interactions among options and paybacks (Rosenzweig and Tubiello, 2007; Swart and Raes, 2007; Wilbanks and Sathaye, 2007; Kok et al., 2008; IPCC, 2007a, Chapter 18; National Research Council, 2010a)). Current research is examining trade-offs and complementarities between mitigation and adaptation in different sectors. In the energy sector, for instance, Kopytko and Perkins (2011) have examined to what extent the siting of nuclear power plants might constrain future adaptation to sea level rise. Others ask about such issues as adaptation implications of the production of biofuels (La Rovere et al., 2009); agriculture and water (Rosenzweig and Tubiello, 2007; Shah, 2009; Falloon and Betts, 2010; Rounsevell et al., 2010; Turner et al., 2010); conservation (Rounsevell et al., 2010; Turner et al., 2010); use of mitigation programs to finance adaptation (Hof et al., 2009); and the urban environment (Biesbroek et al., 2009; Hamin and Gurran, 2009; Roy, 2009; Romero-Lankao and Wilbanks, 2011; Viguié and Hallegatte, 2012).

20.4. Contributions to Resilience through Sustainable Development Strategies and Choices

Although climate change responses can contribute significantly to climate-resilient development pathways, some of the key elements of resilience lie in sustainable development implementation, which can make resilience either more or less achievable. Examples of ways that development strategies and choices can contribute to climate resilience include being capable of resolving trade-offs among economic and environmental goals (e.g., Bamuri and Opeschoor, 2007), ensuring effective institutions in developing, implementing, and sustaining resilient strategies, and enhancing the range of choices through innovation (e.g., Folke et al., 2002; Chuku, 2009; Hallegatte, 2009).

20.4.1. Resolving Trade-offs between Economic and Environmental Goals

Sustainable development pathways will be more climate resilient if they develop and utilize socioeconomic and institutional structures that are effective in resolving trade-offs among social, economic, and environmental goals—a central tenet of sustainable development (Section 20.2.1.1). As climate change poses risks to goals such as poverty reduction, food and livelihood security, human health, and economic prosperity (Chapter 19), societies face the task of defining how to manage these risks and what levels of risk without compromising what they value most and what defines their societies. The management of risk—and the weighting of various categories of risk—depends on social definitions of what consequences are acceptable, tolerable, or intolerable (Chapter 16).

There is a long-standing assumption that economic growth is in conflict with environmental management (Victor and Rosenbluth, 2007; Hueting, 2010). Much of this thinking can be traced back to Malthus and his assertions that population growth (and associated consumption) would expand at an increasing rate until the limits of the Earth's capacity were reached (Malthus, 1798). The very idea of sustainable development itself springs from a need to respond to such Malthusian ideas. The views expounded in the Brundtland Report, for example, are that development should not be unconstrained but should rather be modified into a "sustainable" form (WCED, 1987). Views about relationships between economic growth and environmental protection range widely from arguments that sustainable development is inconsistent with continued economic growth (e.g., Robinson, 2004) to arguments that economic growth and associated technological innovation can enhance options for environmental management (Lovins and Cohen, 2011). Relationships between affluence and environmental protection are complex, as poverty can lead to land degradation and affluence can afford support for nature preservation, while economic growth is built on levels of resource extraction and use that require significant changes in environments. Sustainable development cannot escape continuing tensions between economic growth and environmental management goals, where strongly held views across society often differ so fundamentally that conflict results unless social processes and institutional mechanisms are effective in resolving a host of trade-offs (Boyd et al., 2008), with both values and processes varying according to development context.

Examples of frameworks of thought often related to addressing trade-offs are multi-metric valuation and co-benefits (see also Ness et al., 2007, regarding tools for sustainability assessment; Bizikova et al., 2008, Appendix 1; Gulledge et al., 2010):

- *Multi-metric valuation*. In evaluating development pathways, there are often needs to combine a number of dimensions associated with different valuation metrics and information requirements, such as monetary measures of returns and non-monetary metrics of risk.

Fields ranging from aquatic ecology to risk assessment and financial management have developed tools for such complex valuations, including graphical mapping (e.g., Sheppard and Meitner, 2005; Rose, 2010; Moed and Plume, 2011; UNFCCC, 2011) and the construction of multi-metric indexes (e.g., Johnston et al., 2011). Multi-metric indicators have been widely studied and critiqued, and they are an active topic of research (e.g., Drouineau et al., 2012; Schoolmaster, 2013). A key challenge is weighting different valuations being combined quantitatively, which may be addressed in part by constructing multiple indices. More commonly in collective decision making, however, analytical-deliberative group processes are used to evaluate, weight, and combine different dimensions and metrics qualitatively (National Research Council, 1996).

- *Co-benefits*. An issue in both climate and development policy, related in some cases to access to financial support (e.g., Miller, 2008), is the fact that a specific resilience-enhancing action may have benefits for both development and for addressing concerns about climate change. International funding for mitigation projects has often adopted the concept of "additionality," which takes the position that financial support should be limited to those climate change response benefits that are *in addition to* what would be happening in development processes otherwise (e.g., Muller, 2009). This general concept (e.g., "incremental" costs and benefits) has been applied in financial support for adaptation as well. A co-benefits approach, on the other hand, takes the position that actions that benefit *both* development and climate change responses simultaneously should be encouraged and that a combination of both kinds of benefits should increase the attractiveness of a proposed action (Section 20.3.3). Co-benefits of mitigation actions, such as health benefits, have been extensively analyzed (e.g., Younger et al., 2008; Netherlands Environmental Assessment Agency, 2009; WHO, 2011; EPA, 2012), and they are being actively explored for adaptation as well (e.g., National Research Council, 2010a; UNFCCC, 2011).

As an example of co-benefits, mechanisms such as REDD+ have the potential to achieve both carbon emissions reduction and to benefit livelihoods of those living in forested areas, as well as supporting benefits to social equity (Anglesen et al., 2009; UNEP, 2013). As one instance, the government of Ethiopia has recognized the multiple benefits that can be derived and has incorporated a REDD+ initiative in critical sectors of the economy to develop an environmentally sustainable growth path in Ethiopia (FDRE, 2011). Tools for analyzing such issues are associated with research on "externalities" (e.g., Baumol and Oates, 1988; Klenow and Rodriguez-Clare, 2005; also see Chapter 17 and multi-metric valuations above), but participative planning and decision making usually incorporate a co-benefits perspective as a matter of course.

In practice, trade-offs between different development goals (Stoorvogel et al., 2004) may or not be resolved in coherent ways (Metz et al., 2002). In many cases, resolutions emerge through untidy social processes of evolution and attrition, reflecting dynamics of values, power, control, and surprises, rather than through formal analysis (Bizikova et al., 2008). In some cases, trade-offs are addressed with the assistance of scenario development, the creation of descriptive narratives, and other projections of future contingencies (IPCC, 2012, Chapter 8), along with participative vulnerability assessments (National Research Council, 2010a).

20.4.2. Ensuring Effective Institutions in Developing, Implementing, and Sustaining Resilient Strategies

Climate-resilient pathways will benefit from institutions that are effective and flexible in the face of a wider range of challenges, of which climate change is only one (Gupta et al., 2010). Governance systems, including public and private organizations, will need resources (e.g., human, financial, political, technological) to enable vulnerable societies that are sensitive to the impacts of climate change to transform their lives. Effective management of natural capital and ecosystem goods and services can be accomplished only where there are strong institutions as stewards and a regulatory force to ensure that vulnerable communities are protected from climate shocks and stresses and that growth from climate change is inclusive (Mitchell and Tanner, 2006). Moderating the impacts of climate change will also require strong a foundation in science and technology; but the deployment of science and relevant technologies cannot take place in a vacuum. It will need effective institutional arrangements to bolster both adaptation and mitigation demands and to combine technology options with local knowledge (Section 20.4.3).

"Institutions" refer not only to formal structures and processes but also to the rules of the game and the norms and cultures that underpin environmental values and belief systems (see Glossary). Ostrom (1986) defines institutions as the rules, norms, and practices defining social behavior in a particular context—the action arena. Institutions define roles and provide social context for action and structure social interactions (Hodgson, 2003). Definitions of sustainability are shaped largely by institutional values, cultures, and norms. Institutions also critically influence our ability to govern and manage the resources and systems that shape adaptation, mitigation, and sustainable development. Fostering climate-resilient pathways requires strong institutions that are able to create an enabling environment through which adaptive and mitigative capacities can be built (IPCC, 2007a, Chapter 20; Gupta et al., 2010). Implicit in institutional resilience is the capacity of the exposed unit and the players within an action arena to devise rules that allows them to recover from environmental shocks, and equally ones that provide incentives and benefits that equitably distribute resources across social groups (Handmer and Dovers, 1996; McSweeny and Coomes, 2011). Hence, the trajectory to a climate-resilient pathway requires institutional arrangements that foster innovation, monitoring, and evaluation of strategies for managing climate impacts and reducing risks.

Transformative action within a framework of climate-resilient pathways is rooted in strong and viable institutions and in an institutional context that adaptively manages the allocation of resources and processes of change. Institutions at different levels are the object of societal pressures and challenges relating to environmental change. Local institutions are particularly adroit in coping with multiple changes. These changes often force local actors and organizations to rethink their institutional arrangements and make adjustments that will allow them to cope with multiple vulnerabilities (McSweeny and Coomes, 2011), and their bottom-up initiatives are critically important to climate-resilient pathways. Organizational mechanisms are central to building linkages between local level adaptation action and national level planning. In six case studies in West Africa and Latin America, Agrawal et al. (2011) found that these connections are missing in all the countries studied. However, in these countries external policy support catalyzed adaptation actions through three types of intervention mechanisms: information, incentives, and institutions.

Local institutions crucially influence the ability of communities to adapt and benefit from adaptation and mitigation programs in rural and urban settings (Corbera and Brown, 2008; Chhartre and Agrawal, 2009; Agrawal, 2010). For instance, institutions tend to play an influential role in shaping farmers' decisions and helping them make strategic choices with several implications for livelihoods and sustainable development (Agrawal, 2010). In rural areas, current socioeconomic dynamics, rapid population growth, commercialized agriculture, new agricultural trends, and technological advancements in agriculture have meant that local organizations and actors have seen a change in their role managing environmental resources; local institutions are themselves in a state of flux as they are subjected to uncertainties in climatic condition (Senaratne and Wickramasinghe, 2010). However, in developing countries, particularly in Africa, where traditional knowledge could potentially moderate this uncertainty, it is often not recognized as a reference point for managing climate risks and emerging threats. In Kenya, the importance of indigenous knowledge, given increased uncertainty and climate-related risks, has compelled national agencies such as the Kenyan Meteorological Agencies and vulnerable groups such as the indigenous communities commonly known as rainmakers to form strategic reciprocal links. By working closely together to calibrate their forecasts and test the efficacy of the results against climate change impacts on agricultural productivity, the two groups have been able to demonstrate the benefits of Western science and traditional knowledge systems to increase effectiveness (Ziervogel and Opere, 2010). In integrating different kinds of knowledge, participatory processes, which call for a deliberative form of decision making among stakeholders, are well suited to the governance culture necessary for effective adaptation and mitigation. However, findings in the literature regarding the effectiveness of participatory processes are mixed. For example, though some scholars have argued that deliberative democracy methods can bring diverse stakeholders and kinds of knowledge (e.g., lay, expert, and indigenous) together thus putting in place a more communicative model of science delivery (Benn et al., 2009), empirical research shows that stakeholder participation does not always lead to consensus (Rowe and Frewer, 2004; Bell et al., 2011; also see Salter et al., 2010).

In addition, better institutions are needed to handle the large flows of funds and other resources that are associated with managing and improving the delivery systems that will allow people and organizations to take advantage of opportunities that will trigger a set of actions to combat the negative impacts of climate change. The complexity of different resource flows and distributional effects related to adaptation and mitigation is at the heart of the sustainable development debate, with numerous implications for equity and justice (O'Brien and Leichenko, 2003; Roberts and Parks, 2006). The nature and dynamics of climate change call for flexibility to "allow society to modify its institutions at a rate commensurate with the rapid rate of environmental change" (Gupta et al., 2008). Here, institutional "renewal" is essential to achieve a degree of social cohesion and transformation.

An institutional response to climate change is even more fundamental in common pool property resources such as freshwater, especially because in a changing climate, many river basins are subjected to increased precipitation or water scarcity that affects both their ecosystems and the resources that support the livelihoods of those communities dependent on them. The quality and performance of the organizations and mechanisms created to manage these resources are largely shaped by the rules they follow and the suitability of these rules to the social ecological system in which they are embedded (Bisaro et al., 2010). Indeed, a climate-resilient pathway is one that will not only manage biophysical changes, but also address inherent institutional asymmetries that can further reinforce current inequalities in the way common pool resources are managed. In this context, the monitoring and mediation capacities and the degree to which resource management organizations are embedded at different scales across the governance regime will largely shape its adaptive capacity and sustainability. Thus, the vulnerability of large river basins will largely depend not only on the changing biophysical conditions, but also on institutional architecture that is put in place to manage risks and build resilience. For example, Schlager and Heikkila (2011) argue that compacts that have fixed allocation rules tend to exhibit greater vulnerability to climate change mainly because the system is far too rigid and does not allow for much flexibility in dealing with the changing hydrologic regime. States such as Colorado in the USA have dealt with water scarcity more efficiently mainly because users of the basin have access to venues that allow them to design and review current rules (Schlager and Heikkila, 2011).

Common problems with institutional arrangements for adaptively managing natural resources include a frequent incompatibility of current governance structures with many of those that may be necessary for promoting social and ecological resilience. For example, some major tenets of traditional management styles have "in many cases operated through exclusion of users and the top-down application of scientific knowledge in rigid programmes" (Tompkins and Adger, 2004, p. 10).

20.4.3. Enhancing the Range of Choices through Innovation

Finally, climate resilience will in most cases depend on innovation, developing new ideas and options or adapting robust familiar ideas and options to meet emerging new needs and to respond to surprises (see also WGIII AR5 Chapter 6). As indicated in the previous section, integrated strategies for climate resilience can benefit from considering possibilities to develop new options through social, institutional, and technological innovation. For example, if a climate-resilient pathway for a particular region calls for coping with greater water scarcity, innovations might consider changes in water rights practices, improving the understanding of groundwater dynamics and recharge, improving technologies and policies for water use efficiency improvements, and in coastal areas the development of more affordable technologies for desalination (Lebel, 2005; National Research Council, 2010a). One key issue for risk management, therefore, is assessing needs for and possible benefits from targeting innovation efforts on critical vulnerabilities.

Innovations can include both technological and social changes, which in many cases are closely related (Rohracher, 2008; Raven et al., 2010), as technology and society evolve together (Kemp, 1994). An important characteristic of such socio-technical transitions are the interactions and conflicts between new, emerging systems and established regimes, with strong actors defending business-as-usual (Kemp, 1994; Perez, 2002; IPCC, 2012).

Effective use of innovations depends on more than idea and/or technology development alone. Unless the innovations, the skills required to use them, and the institutional approaches appropriate to deploy them are effectively transferred from providers to users, effects of innovations—however promising—are minimized (IPCC, 2012). Challenges in putting science and technology to use for sustainable development have received considerable attention (e.g., Nelson and Winter, 1982; Patel and Pavit, 1995; National Research Council, 1999; International Council for Science, 2002; Kristjanson et al., 2009). These studies emphasize the wide range of contexts that shape both barriers and potentials and the importance of "co-production" of knowledge, integrating general scientific knowledge with other forms of knowledge (e.g., local, indigenous, practical knowledge, experience, and expertise). If obstacles related to intellectual property rights can be overcome, however, the growing power of the information technology revolution could accelerate the transfer of technologies and other innovations (linked with local knowledge) in ways that would be very promising for strengthening local resilience (Wilbanks and Wilbanks, 2010).

New technologies have the potential to allow a number of developing countries to benefit from knowledge in ways that will give them considerable advantage in building the relevant social and institutional infrastructure to sustain a climate-resilient pathway. Advances in mobile technologies in developing countries, for example, have increased the accessibility of farmers to critical information such as disease surveillance, information related to agricultural inputs, and market prices for crops (Hazell et al., 2010; Juma, 2011). Biotechnology applications in biological systems have the potential to lead to increased food security and sustainable forestry practices, as well as improving health in developing countries by enhancing food nutrition.

20.5. Determinants of Resilience in the Face of Serious Threats

Climate change is not the only type of change occurring in the 21st century. Many households, communities, organizations, countries, and regions are confronting a confluence of economic, political, demographic, social, cultural, and environmental changes. Issues such as poverty, economic crisis, increasing inequality, and violent conflict often draw attention away from concerns about climate change, the loss of biodiversity and ecosystem services, and other global environmental issues. However, the impacts of climate change and extreme events can exacerbate food insecurity, slow down the pace of poverty reduction in urban areas, influence human health, and jeopardize sustainable development (Chapters 11, 12, 13). Resilience is a concept that takes into account how systems, communities, sectors, or households deal with disturbance, uncertainty, and surprise over time, and it is characterized by both adaptability and transformability (Walker and Salt, 2006; Folke et al., 2010; Westley et al., 2011). The sections below consider two important components of climate-resilient pathways: transformational adaptation in response to the impacts of climate change, and transformational change to reduce vulnerability and the risk of high-magnitude climate change.

20.5.1. Relationships between the Magnitude and Rate of Climate Change and Requirements for Transformational Adaptation

The timing and ambition levels of global GHG mitigation efforts will influence the magnitude and rate of climate change and its impacts, particularly in the second half of the 21st century and beyond (Kriegler et al., 2012; Peters et al., 2013; Rogelj et al., 2013; see also Box 20-3). Model results based on integrated scenarios that take into account geophysical, technological, social, and political uncertainties indicate that reaching the often-discussed limit of a 2°C average global temperature increase calls for mitigation of emissions through increased energy efficiency and lower energy demand well before 2020 (Peters et al., 2013; Rogelj et al., 2013; see also Section 20.6.1). If the magnitude and rate of climate change is kept minimal or moderate, incremental adaptation may be a sufficient response to consequences in many locations and contexts. However, in cases where vulnerability is currently high, transformational adaptation may be needed to respond to changes in climate and climate variability. In the absence of ambitious mitigation efforts, the impacts of climate change can be expected to increase dramatically from the second half of the 21st century onward (see Chapter 19). In this case, transformational adaptation may be required in advance of disruptive impacts to reduce risks and vulnerabilities (Kates et al., 2012).

This distinction between incremental and transformational adaptation is important: incremental adaptation can be considered extensions of actions and behaviors that already are in place to reduce losses or enhance benefits associated with climate change, often where the goal is to maintain the essence and integrity of an existing system or process at a given scale (Kates et al., 2012; Park et al., 2012). Transformational adaptation, in contrast, includes actions that change the fundamental attributes of a system in response to actual or expected impacts of climate change. These may involve adaptations at a larger scale or greater intensity than previously experienced; adaptations that are new to a region or system; or adaptations that transform places or lead to a shift in the location of activities (Kates et al., 2012). Such transformations are expected to occur when the rate and magnitude of climate change threatens to overwhelm the resilience of existing systems, or when vulnerability is high (Kates et al., 2012). Transformational adaptation often occurs in continuous interaction with incremental adaptations (see IPCC, 2012, Figure 8-1; Park et al., 2012). Although thresholds or tipping points in complex systems are difficult to predict, studies from a variety of disciplines indicate some generic properties associated with transitions between different states, including an increase in recovery times from disturbances such as extreme weather events (Scheffer et al., 2009; Lenton, 2011a). The risks associated with a high magnitude and rate of climate change and its impacts on natural and managed resources and systems are considerable. The limits to adaptation (Chapter 16) suggest that transformational change may be a requirement for sustainable development in a changing climate (Westley et al., 2011; O'Brien, 2012).

20.5.2. Elements of and Potentials for Transformational Change

Transformational change can be considered a means of reducing risk and vulnerability, not only by adapting to the impacts of climate change, but also by challenging the systems and structures, economic and social relations, and beliefs and behaviors that contribute to climate change and social vulnerability. In cases where current development pathways are considered as the root causes of climate risk and vulnerability, transformation of wider political, economic, and social systems may be necessary (Pelling, 2010; IPCC, 2012; Lemos et al., 2013).

Transformation is defined as a change in the fundamental attributes of natural and human systems (see Glossary). Within the WGII AR5, transformation could reflect strengthened, altered, or aligned paradigms, goals, or values towards promoting adaptation for sustainable development, including poverty reduction. Transformations can occur quite suddenly, in response to a specific event or a momentous incident, or they may emerge gradually over time (Loorbach, 2007). Transformational change is often difficult to order or plan, and there are many social, political, and cultural barriers and resistances. Transformational change can threaten vested interests, or prioritize the interests of some over the well-being of others, and it is never a neutral process (Meadowcroft, 2009; Smith and Stirling, 2010). At the national level, transformation is considered most effective when it considers a country's own visions and approaches to achieve sustainable development in accordance with their national circumstances and priorities. While not every transformation is considered ethical, equitable, or sustainable, it is possible to promote deliberate transformations that reduce climate risk and vulnerability and contribute to global sustainability (Folke et al., 2010; Kates et al., 2012; O'Brien, 2012).

There is an extensive literature on transitions and transformations covering a variety of sectors and factors that influence changes in systems and behaviors (Geels, 2002; Calvin et al., 2009; Berkhout et al., 2010; Pelling 2010; Shove and Walker, 2010; WGIII AR5 Chapter 6). Transformations can be promoted by creating enabling conditions, which include a supportive social environment, information flows, and access to options, resources, and incentives for change (Kates et al., 2012). Transformations can also be stimulated through rules and regulations that necessitate innovations, alternative options, or new behaviors. Finally, transformations may result when alternative systems and structures eventually make old ones seem outdated. Often, dramatic focal events can draw attention to the need for change and mobilize groups or networks to advocate transformational change (Hernes, 2012).

Transformation processes are linked to learning, leadership, empowerment, and collaboration within and across institutions, organizations, and groups (Heifetz et al., 2009; IPCC, 2012, Chapter 8; Kates et al., 2012; O'Brien, 2012). Other key elements associated with transformations include adaptable institutions (cultural, economic, and governance), all types of capital, diversity in landscapes, seascapes and institutions, learning platforms, collective action and networks, as well as reflexivity and the capacity to take different perspectives (Loorbach 2007; Folke et al., 2010; Schlitz et al., 2010; Westley et al., 2011). Many of the elements of climate-resilient pathways discussed in Box 20-3 can, in fact, support transformation.

Transformations can take place within diverse realms or spheres (see Figure 20-2). Within each sphere, there exist both catalysts and constraints to transformation. The core of transformational change occurs in what is labeled in Figure 20-2 as the "practical sphere." Here,

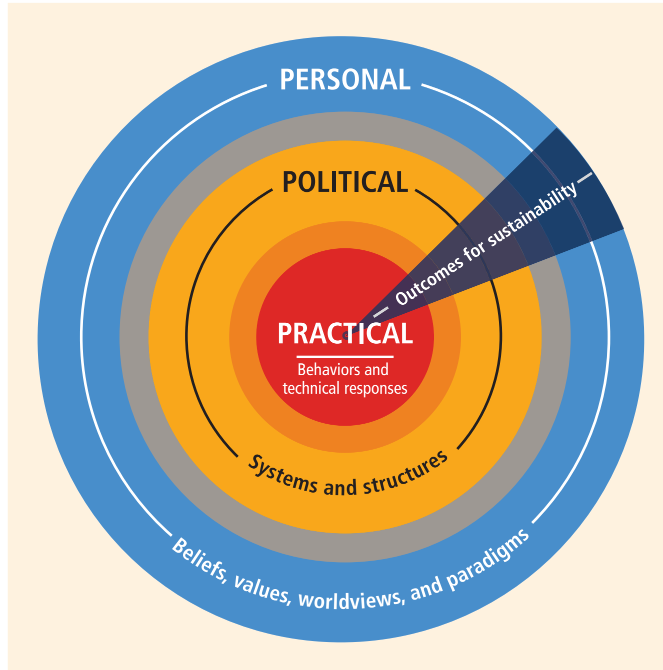

Figure 20-2 | The three spheres of transformation. Transformational change may be an effective leverage point for promoting climate-resilient pathways for sustainable development. This figure depicts three interacting spheres or realms where transformational changes toward sustainability may be initiated. Transformations in the outer two spheres can have a large influence on behaviors and technical responses, contributing to nonlinear transformations to sustainability (O'Brien and Sygna, 2013).

measures such as technological innovations and economic incentives are used to influence sustainable behaviors and responses. The outcomes of transformations in this sphere are observable and measurable; many sustainability policies and initiatives target transformations in this sphere. However, these transformations are often constrained by larger systems and structures, including financial, political, legal, social, economic, ecological, and cultural systems that define the boundaries for action. The "political sphere" is where systems and structures are transformed (intentionally or unintentionally) through politics and social movements, or through changes in social and cultural norms and power relations. Systems and structures often reflect dominant cultural beliefs and worldviews, and it is here where value conflicts may be experienced or resolved. A third sphere of transformation is the "personal sphere," which includes individual and collective beliefs, values, and worldviews, as well as the dominant paradigms. Transformations in this sphere can influence systems, structures, behaviors, and responses, and thus they represent important leverage points for sustainability. Attention to transformations in all three spheres is considered necessary in response to the observed and anticipated impacts of climate change (Beddoe et al., 2009; O'Brien and Sygna, 2013).

20.6. Toward Climate-Resilient Pathways

20.6.1. Alternative Climate-Resilient Pathways

Climate-resilient pathways consist of future trajectories of development that combine adaptation and mitigation in the context of sustainable development implementation. At any scale (local or regional) there are alternative paths leading to similar levels of climate resilience (Holling, 1973). At any time along a pathway, more or less resilience may be observed at specified points within the system (or locality), while the total amount of resilience within the entire system remains unchanged (Folke, 2006). Each potential alternative pathway can be strengthened and evaluated based on certain risk management characteristics/elements: the capacity to (1) foresee risk/vulnerability; (2) decrease climate change impacts; (3) respond rapidly to unpredictable, uneven, and extreme events; (4) include considerable amounts of proactive adaptation; and (5) evolve in support of societal advancement and balanced environmental management.

Examples in this chapter demonstrate that many of the choices involved in framing and supporting attempts to increase and sustain climate resilience are made largely at global and national levels, but many of the actions to sustain resilience are made at local levels. The global pathways that emerge are accumulations of these local and national choices. In these processes, path dependence is strong enough such that risk management decisions in the near term are more likely to lead to resilience if long-term objectives are included as well as a wider spatial scale up to and including the global level.

A central issue in considering alternative pathways is the extent to which they may fail to meet a criterion of climate resilience. Or to put the question more simply, "are there any boundaries on the envelope of climate resilience?" The answer is highly scale dependent. We have a carbon legacy in the atmosphere, and total prevention/avoidance of impacts is now unachievable (Dickinson, 2007). At any level of stabilization of GHG concentrations, with even the strongest emissions reduction targets, some localities or systems or populations will be vulnerable to disruptions because there is in effect no limit below which universal prevention of residual loss and damages can be assured. Transformational change will therefore need to be a key component in nearly all alternative climate-resilient pathways.

In the event that global surface mean temperatures rise through +2°C to +4°C and higher (Anderson and Bows, 2008; Schneider, 2008; New et al., 2012), sustainability will become significantly more difficult to achieve (food security is a notable example; see Chapter 7). For example, a business-as-usual future society where unsustainable development paths are the norm, where technology transfer between countries is lacking, population growth increases rapidly, GHG emission go unabated, and institutions and governance structures are ineffective at creating effective climate change policies, would almost certainly result in losses so widespread that a development pathway would not be resilient (Riahi et al., 2011; Arnell et al., 2013). A pathway that included these elements would fall outside the "boundaries of the envelope of climate resilience."

Within these boundaries, climate-resilient pathways can be made up of a collective of alternative choices at the regional level, where they are dependent upon specific demographics, potentials for economic development and growth, ecological and ecosystem services, access to natural resources, institutional and governance structures, and technological development and transfer. This concept at the global level offers a conceptual framework for considering alternative mixes of actions in support of climate resilience. Pathways can be developed to illustrate a range of possible futures, as a basis for discussion, following different yet distinct storylines. These dimensions can then be related to socioeconomic challenges confronting climate change mitigation and adaptation (as one aspect of sustainable development). One such pathway could have relatively limited challenges to both adaptation and mitigation, while another has substantial challenges to both adaptation and mitigation. Any pathway characterized by low challenges to both has a high potential to be more climate resilient at the global scale and in many local or national situations. A pathway characterized by high challenges to both adaptation and mitigation has a high potential to be less climate resilient at the global scale and in many localities and countries.

20.6.2. Implications for Current Sustainable Development Strategies and Choices

Decision makers face an array of choices in their efforts to define and implement pathways that will help to improve human well-being now and in the future in the face of climate change and other stressors.

Although payoffs from specific long-term pathways may be uncertain at this time, growing evidence (IPCC, 2007; see also Chapters 8 to 13, 16 to 19) suggests that decision points and actions are at hand now. Climate-resilient development pathways are not only about actions taken in the future, but they are also about strategies and choices that are taken today. In fact, damage and loss patterns are not limited to future vulnerabilities; in many areas they are impeding food production and other essential development services in ways that deepen and widen poverty (Chapter 13), contribute to involuntary migration (Chapter 12; Warner and Afifi, 2013), and pressure food production and food prices (Chapters 7, 17; Warner and van der Geest, 2013).

In this sense, delaying action in the present may reduce options for climate-resilient pathways in the future. In some parts of the world,

Frequently Asked Questions

FAQ 20.4 | Are there things that we can be doing now that will put us on the right track toward climate-resilient pathways?

Yes. Climate-resilient pathways begin now, because it is time to consider possible strategies that would increase climate resilience while at the same time helping to improve human livelihoods and social and economic well-being. Combining these strategies with a process of iterative monitoring, evaluation, learning, innovation, and contingency planning will reduce climate change disaster risks, promote adaptive management, and contribute significantly to prospects for climate-resilient pathways.

inadequate efforts to address effects of emerging climate stressors are already eroding the basis for sustainable development. New studies find that among people who attempt to cope with current stresses, most experienced negative residual impacts and as a consequence faced eroding household income and food security, health, and education opportunities and were more likely to migrate and lose housing and livelihood assets (Monnereau and Abraham, 2013; Rabbani et al., 2013; Traore et al., 2013; Warner and van der Geest, 2013; Yaffa, 2013). For example, in the Punakha district in Bhutan, 87% of households that adopted coping measures reported that they were still experiencing adverse effects of changing monsoon patterns despite the adaptation measures (Kusters and Wangdi, 2013). Evidence (Chapters 7, 8, 12, 13, 16, 19) suggests that waiting to take more effective action may reduce the range of choices for climate-resilient pathways in the future (National Research Council, 2011).

More generally, IPCC (2012) makes the case that a window of opportunity exists now for considering possible strategies that would increase climate resilience while at the same time helping to improve human livelihoods and social and economic well-being. It suggests that a process of iterative monitoring, evaluation, learning, innovation, and contingency planning will reduce climate change disaster risks, promote adaptive management, and contribute significantly to prospects for climate-resilient pathways. In this sense, strategies and actions can be pursued now that will move toward climate-resilient pathways while at the same time helping to improve human livelihoods, social and economic well-being, and responsible environmental management.

As policy makers explore what pathways to pursue, they will increasingly face questions about managing discourses about what societal objectives to pursue unchanged, where compromises in objectives are tolerable, and what consequences including loss and damage may be associated with different pathways. In considering possible needs for transformational pathways (Section 20.5), extreme weather occurrences such as major floods, wildfires, cyclones, and heat waves may focus societal attention on vulnerabilities and stressors and provide a "policy window" for major changes (Kingdon, 1995; Birkland, 2006; Kates et al., 2012). Discussions of transformation may require broader-based social discourse (Pelling et al., 2007) and iterative institutional learning (Berkhout et al., 2006), on the basis of growing evidence, knowledge, and experience. Systems to monitor emerging stresses and threats will aid decision makers at different scales to evaluate alternative pathways (Kates et al., 2012).

20.7. Priority Research/Knowledge Gaps

Because integrating climate change mitigation, climate change adaptation, and sustainable development is a relatively new challenge, research should be a very high priority indeed to inform strategies and actions. The most salient research need is to improve the understanding of how climate change mitigation and adaptation can be combined with resilient sustainable development pathways in a wide variety of regional and sectoral contexts (Wilbanks, 2010). One starting point is simply improving the capacity to characterize benefits, costs, potentials, and limitations of major mitigation and adaptation options, along with their external implications for equitable development, so that integrated climate change response strategies can be evaluated more carefully (Wilbanks et al., 2007; National Research Council, 2011). What are the major trade-offs? What are the potential synergies? How do implications of integrated mitigation/adaptation strategies vary with location, climate change risks and vulnerabilities, scale, and development objectives and capacities (e.g., Hugé et al., 2011)? In these regards, the best of global science needs to be combined with national and local expertise to advance knowledge related to climate-resilient pathways.

Related to this general priority are at least three specific research needs:

- Advances in conceptual and methodological understandings of, and tools to support research on, multiple drivers of development pathways and climate change impacts; possible feedback effects among mitigation, adaptation, and development; possible thresholds/tipping points that could cause particular challenges for development; and possible transformations to reduce losses and damages and support sustainable development (Stern and Wilbanks, 1999; National Research Council, 2010a; see also Section 20.5).
- Advances in knowledge about how to respond sustainably to climate change extremes and extreme events, when and where they pose development challenges that would appear to require transformative changes in affected human and/or environmental systems. What might the response options be, and how can they be facilitated where they merit consideration (e.g., Pelling, 2010; Lemos et al., 2013)?
- Research on how to reconcile the importance of synergies between climate change adaptation and mitigation actions with widespread use of the concept of "additionality." For example, how might criteria be established for access to financial support for adaptation that incorporates the development importance of co-benefits? Such research could inform discourses about differences between adaptation and development in ways that enable the flow of financial resources to support adaptations (National Research Council, 2010a).

Further research needs include:

- Research attention to potentials for technological and institutional innovations to ease threats to sustainable development from climate change impacts and responses. In other words, how might climate change responses represent opportunities for innovative development paths? How might technological development be part of a strategy for development/climate change response integration (Wilbanks, 2010)?
- Research on strategies for institutional development, including improving understanding of how social institutions affect resource use (Stern and Wilbanks, 1999), improving understanding of risk-related judgment and decision-making under uncertainty (Stern and Wilbanks, 1999), and best practices in creating institutions that will effectively integrate climate change responses with sustainable development characteristics such as participation, equity, and accountability.
- Research on strategies for the implementation of adaptive management and risk reduction for development. Examples of important research needs include improving the understanding of respective roles and interactions between autonomous response behavior and policy initiatives; improving the body of empirical evidence about how to implement changes that are judged to be desirable, for example, adaptive management and governance capacity; and improving the understanding of differences between

retrofitting older infrastructures (challenge in many industrialized countries) and designing new infrastructures (challenge in many rapidly developing countries) (IPCC, 2012, Chapter 8).
- Research to improve the understanding of how to build social inclusiveness into development/climate change response integration. As suggested above, research is needed on issues of social values/climate justice/equity/participation and how they intersect with the deployment of mitigation, adaptation interventions, and sustainable development policy in different regional/sociopolitical contexts (IPCC, 2012, Chapter 8).
- Research on factors that influence deliberate transformations that are ethical, equitable, and sustainable (Kates et al., 2012; O'Brien, 2012).
- The development of structures for learning from emerging integrated climate change response/development experience, for example, approaches and structures for monitoring, recording, evaluating, and learning from experience and identifying "best practices" and their characteristics (National Research Council, 2010a; Hilden, 2011; IPCC, 2012, Chapter 8).

Finally, it is very possible that progress with global climate change mitigation will not be sufficient to avoid relatively high levels of regional and sectoral impacts, and that such conditions would pose growing challenges to the capacity of adaptation to avoid serious disruptions to development processes. If this were to become a reality later in this century, one response could be a rush toward geoengineering approaches. In preparation for such a contingency, and perhaps as an additional way to show how important progress with mitigation will be in framing prospects for sustainable development in many contexts, there is a very serious need for research on geoengineering costs, benefits, risks, a wide range of possible impacts, and fair and equitable structures for global policy and decision making (UK Royal Society, 2009; Kates et al., 2012).

But a fundamental aim of research to improve capacities for climate-resilient pathways for sustainable development is to avoid such an unfortunate outcome. It seeks to do so by strengthening the base of knowledge that underlies and supports effective actions by viewing climate change mitigation, climate change adaptation, and sustainable development in an integrative and mutually supportive way.

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