Potential Impacts of Climate Change on Biodiversity

in Central America, Mexico, and the Dominican Republic

USAID
FROM THE AMERICAN PEOPLE

CATHALAC

2008

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FOREWORD

International efforts to mainstream sustainable environmental management into national economic development came to a head in the early 1990s, with world attention focused on the interrelationships and impacts among environment, economics, and human development. As a result, two significant United Nations Conventions emerged which set the international standard for sustainable management of natural resources with a view, ultimately, toward the benefit of all humankind. The United Nations Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD) – both products of the 1992 Rio Summit – are now converging and mutually strengthening each other, to the point where it is obvious that synergies, particularly in the field of adaptation to climate change, could enhance our capacity to confront the most challenging problem of the XXI century: the depletion of the very base for the survival of the human species.

Biodiversity, at the level of individual species, is facing a changing climate which threatens to transform the functions of the ecosystems. Climate change is a global problem which will affect ecosystems differentially. Today, the ecosystems of Mesoamerica and the Caribbean are undergoing a process of transformation caused by changes in temperature, rainfall and sea level rise, resulting in a variety of adverse consequences. Forest fires, the bleaching of coral reefs, the increased spread of tropical diseases and the slow loss of island territories are testimonies of this. The Intergovernmental Panel on Climate Change (IPCC) also affirms that with climate change, species dwelling in montane habitats will become displaced to higher altitudes and latitudes. This therefore forces us to rethink our overall relationship with the natural environment, and the wide-ranging implications for future generations.

Human activities have and continue to cause the loss of biodiversity due to deforestation and land cover conversion, among others: contamination of the air and water, soil degradation and desertification, diversion of water from natural ecosystems to agriculture lands and urban areas, the fragmentation of habitats, depletion of species from overhunting, the introduction of invasive species, and the depletion of the ozone layer.

All is not lost. The year 2010 has been declared the International Year of Biodiversity and the Parties to the CBD have set achieving "a significant reduction of the current rate of biodiversity loss at the global, regional and national levels as a contribution to poverty alleviation and to the benefit of all life on earth" as the goal for that year. Part of achieving that goal requires taking into account the scientific evidence to identify areas likely to be affected by climate change, and to develop the capacity to adapt to climate change.

This study is an effort to better understand how climate change might affect the biological resources our region possesses. In addition to the important scientific findings presented here, this study presents an undeniable opportunity for action, to begin taking the steps to reverse adverse trends. It is our sincere hope that the results of this study are incorporated in the respective National reports to the UNFCCC and the CBD whose preparation is underway.

I take this opportunity to issue heartfelt thanks to the national experts who participated in this process, the United States Agency for International Development (USAID), the U.S. National Aeronautics & Space Administration (NASA), the University of Alabama-Huntsville, Cable & Wireless-Panama and the Environmental Systems Research Institute (ESRI) for their collaboration in the Global Development Alliance (GDA)-sponsored project which produced this publication.

Emilio Sempris

EMILIO SEMPRIS
Director
CATHALAC

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ACRONYMS

ACCII	Adaptation to Climate Change Project
CATHALAC	Water Center for the Humid Tropics of Latin America and the Caribbean
CBD	United Nations Convention on Biological Diversity
CCAD	Central American Commission for the Environment and Development
CCCCC	Caribbean Community Climate Change Center
CCCSN	Canadian Climate Change Scenarios Network
CCSI	Climate Change Severity Index
CGCM3T47	Third generation Coupled Global Climate Model, version T47, from the Canadian Centre for Climate Modelling and Analysis
CSIRO MK3	Mark 3 of the coupled climate model of Commonwealth Scientific and Industrial Research Organization, Australia
CWP	Cable and Wireless, Panama
EARTHSAT	Earth Satellite Corporation
ESRI	Environmental Research Systems, Incorporated
EVCC	Ecosystem Vulnerability to Climate Change
GCM	General Circulation Model / Global Climate Model
GDA	Global Development Alliance program of USAID
GEF	Global Environment Facility
GEO BON	Group on Earth Observations – Biodiversity Observation Network
GEO-LAC	UNEP Global Environmental Outlook – Latin America and Caribbean
GHG	Greenhouse Gas
GIS	Geographic Information Systems
HADCM3	Hadley Centre Coupled Model, version 3
ICRAN-MAR	International Coral Reef Action Network – Mesoamerican Reef Alliance Project
IPCC	Inter-governmental Panel on Climate Change
IUCN	World Conservation Union
MA	Millennium Ecosystem Assessment
MBC	Mesoamerican Biological Corridor
mm	Millimeters of precipitation
NASA	United States National Aeronautics and Space Administration
NCAR	United States National Center for Atmospheric Research
NOAA	United States National Oceanographic and Atmospheric Administration
PRECIS	Providing Regional Climates for Impact Studies
RCM	Regional Climate Model
SERVIR	Regional Visualization & Monitoring System
SDSM	Statistical Downscaling Model
SRES	Special Report on Emission Scenarios of the IPCC
STRI	Smithsonian Tropical Research Institute
UAH	University of Alabama-Huntsville
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development

EXECUTIVE SUMMARY

The recently-published Fourth Assessment Report of the Inter-Governmental Panel on Climate Change (IPCC) suggests that Latin America and the Caribbean will certainly not be left unscathed by such global changes. Within the broader region, Mesoamerica and the Caribbean stand out as their biological resources of are globally significant, putting both sub-regions in the ranks of the world's top twenty-five "biodiversity hotspots." In Mesoamerica alone, 7% of the globe's terrestrial species inhabit less than 1% of earth's landmass. One key concern, therefore, is the impact climate change will have on such globally significant biodiversity. Among other questions, this study seeks to assess the potential impacts of rising temperatures and changing rainfall patterns on the region's species and ecosystems.

Within the geographic domain of Mexico, Central America and the Caribbean, this study utilizes a novel geospatial modeling approach, integrating both climatological and biodiversity data to assess which areas and species might be significantly impacted by imminent changes in precipitation and temperature patterns. High-resolution climatological scenario data from the SERVIR, PRECIS and WorldClim initiatives were variously used as inputs in the analysis, acknowledging that while climate scenario data are not predictions and possess uncertainties, they nonetheless constitute useful tools that can allow Governments, local communities, and international communities to better plan strategies for mainstreaming initiatives to facilitate adaptation to climate change in the region.

According to the modeling work conducted, if worst case scenario conditions prevail, by the 2020s, the Caribbean coasts of lower Central America will be significantly impacted by climate change. Countries that would be affected include Costa Rica, the Dominican Republic, Honduras, Nicaragua and Panama. Furthermore, by the 2080s, in terms of the "comfort zone" of climatic niches that species and ecosystems are tolerant to, if worst case scenario conditions prevail, all of the ecosystems and species of Central America and the Dominican Republic will be subjected to conditions well outside of their traditional "comfort zone," while with the exception mainly of parts of Baja California and the Yucatan, Mexico's ecosystems and species would go largely unaffected. This is because the majority of Mexico's ecosystems already tolerate a relatively wide temperature and precipitation threshold, likely indicating resilience to climate changes that may occur.

Additionally, in terms of the potential climate change impact on existing protected areas, , the ecosystems and species most likely to be affected by are already within protected areas for a large part. One would therefore expect that if these ecosystems continue to be protected, for a variety of reasons, the chances of these ecosystems adapting to climate change would be higher compared to those vulnerable ecosystems currently outside existing protected areas networks.

This analysis also identifies critical areas that may require specific interventions to facilitate the adaptation of species to climate change. It is also worth pointing out, however, that in addition to climate change, ecosystems and species will likely continue to be threatened by deforestation. Expanding from previous climate research that has largely focused on the magnitude of potential climate change, this study also presents a novel framework with which climate change impacts can be assessed in specific natural systems.

INTRODUCTION

Diversity of life

Mesoamerica and the Caribbean are two of the world's twenty-five biodiversity hotspots, teeming with globally significant biological diversity (Figure 1). In Mesoamerica alone, more than 7% of the world's terrestrial species are found on less than 1% of earth's landmass (Barry 2003). Yet, deforestation and uncontrolled human development have resulted in the loss of an estimated 70% of original habitat (Conservation International 2004). In response to this situation, the regions' governments have demonstrated their commitment to biodiversity conservation through the Mesoamerican Biological Corridor and Caribbean Biological Corridor, networks of protected areas spanning the isthmus and Caribbean islands. These corridors are home to the globe's only preserves for sensitive species such as the jaguar and whale shark (respectively the largest cat in the Americas, and the world's largest fish).

Source: "Hotspots Revisited", Conservation International 2004

Figure 1 *Biodiversity hotspots as defined by Conservation International, 2004.*

The climatic advantage

Over millennia, varying climatic patterns and topologies throughout the regions have provided the backdrop in which different types of vegetation flourish. From the abundant sunlight and water arose diverse arrays of ecosystems and species, filling unique and complex systems of niches. In addition to the normal temperature and precipitation regimes, climatic extremes such as hurricanes, tropical storms, floods, and droughts, were also a part of the tapestry in which the regions' species and ecosystems thrived. Even though these natural events cause stress and destruction, they have occurred for thousands of years; as such, ecosystems and species have developed adequate resilience to be able to recover from such phenomena. This resilience is the result of millions of years of evolution, where environmental factors such as temperature and precipitation sculpted landscapes and defined habitats.

The climatic dilemma

The rich tapestry of species and ecosystems in which Mesoamerica and the Caribbean host is constantly threatened by human-induced drivers of environmental change. The conversion of natural landscapes such as forests, grasslands, and wetlands, to agriculture, pastures, or settlements is the primary culprit of habitat loss and the endangerment of species. Our knowledge of humans' capability to transform landscapes is not by any means novel; however, we are becoming more and more aware of our ability to modify the global and local climate. Like land degradation, the anthropogenic emissions of greenhouse gases such as carbon dioxide, methane, and nitrous oxides, puts the regions' biodiversity at risk. Moreover, climatic catastrophes undoubtedly imperil the stability the regions' social and economic infrastructures, and global climate change is expected to further exacerbate such susceptibility. Perhaps we are already seeing this effect because now more than ever—at least in recorded history—have natural and human-made systems been so overwhelmed with hurricanes and tropical storms (Figure 2).

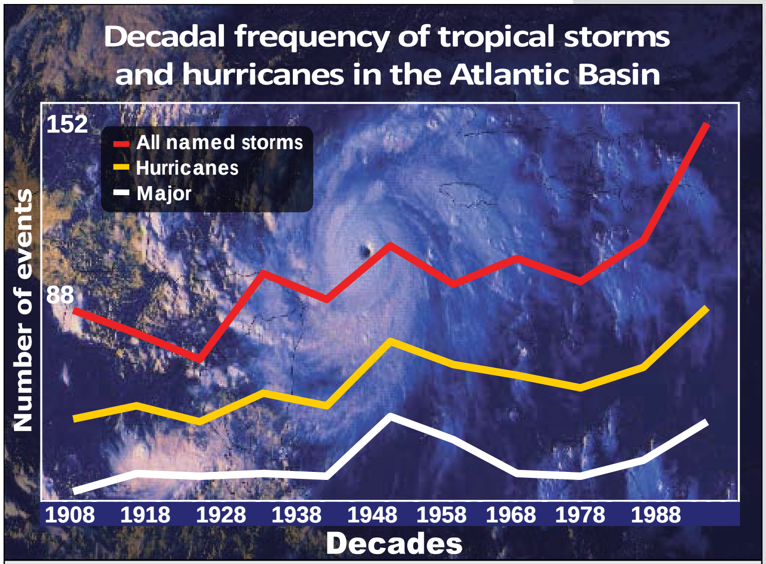


Figure 2 *The decadal frequency of tropical storms and hurricanes during the past 100 years has been 88 events, while the last decade has far exceeded that range at 152. Data derived from NOAA, 2008. Image source: NOAA National Environmental Satellite, 1998.*

Biodiversity comprises many ecosystem services—in the form of plant products that are vital to our regions' livelihoods, an ecosystem that filters out pollutants, or rare species that display the world's beauty. Thus, it is especially important to monitor the possible impacts of climate change on biodiversity.

BACKGROUND

Measuring biodiversity

There is no one universal measure of biodiversity. The methodologies used to evaluate and the subsequent data produced differ for every objective and investigator. Biodiversity can be measured as various changes over time; it can be measured spatially; it can be measured at varying scales—from months to centuries and from cells to continents. In order to incorporate both the Mesoamerican and Caribbean regions in the context of climate change, we must first define what is available in terms of climate scenarios and at what level.

The Convention on Biological Diversity recognizes biodiversity at three levels: genes, species, and ecosystems. In short, genetic studies are useful for assessing evolutionary abilities or intra-species diversity. Populations of species with higher genetic diversity—or a larger gene pool—are expected to be more resilient against outside disturbances. For studies of regional magnitudes, genetic biodiversity is likely out of the question. Because there is an abundance of species that inhabit Mesoamerica and the Caribbean, and because ecosystems determine the habitats of these species, we will focus on these two fields later in the report.

Climate change models & scenarios

Dynamics and impacts of climate change involve complex feedback loops driven by human-produced greenhouse gases emitted into the atmosphere; therefore, it is necessary to develop models that demonstrate potential scenarios in the future. There are in excess of thirty global models that attempt to address this issue, which illustrate possible states of the climate nearly one hundred years into the future. The most sophisticated models include the flow of atmospheric, oceanic, glacial, and terrestrial energy and mass. Each of these models is run numerous times under different conditions, as defined by the Special Report on Emissions Scenarios (SRES), prepared for the Intergovernmental Panel on Climate Change (IPCC). These scenarios represent different circumstances in which our population, economy, technology, energy, and land-use, change and grow. Simply stated, societies can either collaborate in addressing global problems with comprehensive solutions, or they can remain self-interested in solving their isolated problems. Additionally, development interests can be more directed at increasing human wealth, or they can be more concerned with preserving the environment (Figure 3).

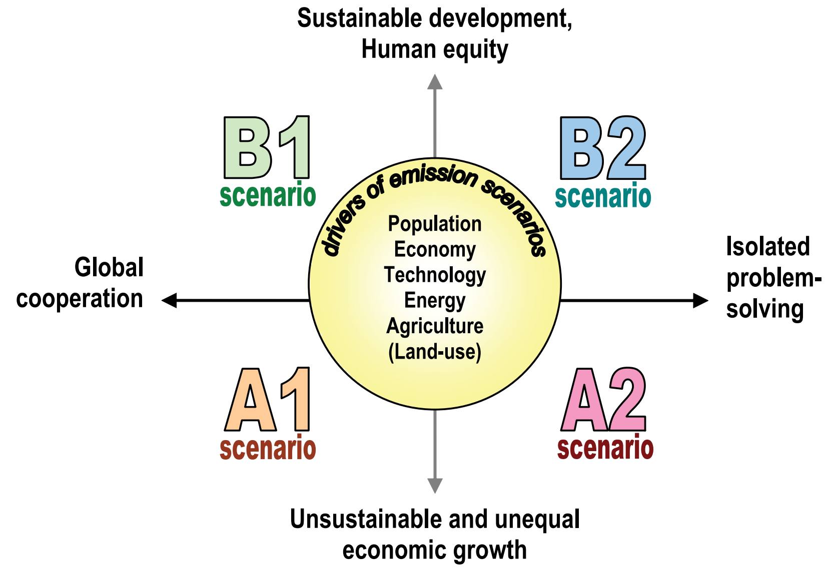


Figure 3
Conceptual breakdown of climate change scenario families. The horizontal axis expresses our means of adapting to problems, and the vertical axis represents the type of development (inspired by SRES 2002).

Under this scheme, each of the A1, A2, B1, and B2, families has their own, more specific scenarios, which makes 40 climate change scenarios. Considering the large collection of scenarios and wide range of modeling organizations, it is easy to see that thousands of climate change projections exist. The development and fine-tuning of such sophisticated models at a global scale is an enormous achievement for the climatological and technical communities; however, a few complications arise when attempting to understand the regional implications of global climate change. First, it is difficult to know which scenarios to choose and how to describe the possible changes. For instance, should one focus on temperature, precipitation, or some other measure? Second, although these models consider the complex interactions between aquatic, terrestrial, and aerial components, and can be tested and proven backwards and forwards in time, they still cannot capture regional and local phenomena that are important to ecosystems, species, and human infrastructure. We will return to these issues later, keeping in mind the requirements for the analysis of biodiversity at regional and local levels.

OBJECTIVES

The overall objective of the current study is **to assess the potential impacts of climate change on the biodiversity of Belize, Costa Rica, the Dominican Republic, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, and Panama.** The study focuses on biodiversity from the standpoint of both ecosystems and the species which inhabit them, particularly terrestrial amphibians, birds and mammals, keeping in mind how climatic factors will potentially impact or threaten these.

Ecosystems represent the dominant vegetation in an area—or the dominant type of land cover if human intervention has occurred. Species richness is a fundamental measure of biodiversity, which counts the number of unique individual species in a place, regardless of the density or abundance or each type of animal. As mentioned before, historic climate is a principal factor in shaping landscapes and determining the extent of species' habitats. Over time, species and ecosystems have adapted to certain ranges, or comfort zones in terms of climate. Climate change is threatening to push environmental conditions outside of many ecosystems' and species' comfort zones. This is a central theme of this study, since it provides the backbone for the Climate Change Severity Index, which is described in further detail.

The final product of this study is the identification of critical habitats: places where climate change is projected to most greatly threaten biodiversity. This is the result of using modeling to combine the species richness distribution with the Climate Change Severity Index. We consider six climate change scenarios from various organizations, each including three projections for the future.

This study is one of the main deliverables to the U.S. Agency for International Development (USAID) Global Development Alliance (GDA) program-funded *"Mainstreaming Climate Indices & Weather Derivatives into Decision-Making for Adaptation to Climate Change in Central America, Mexico and the Dominican Republic"* project. The project is implemented by CATHALAC with the collaboration of USAID, the U.S. National Aeronautics & Space Administration (NASA), the University of Alabama-Huntsville, the Environmental Systems Research Institute (ESRI), and Cable & Wireless-Panama.

METHODOLOGY

The analysis was conducted in four main stages, namely:

1. **Biodiversity: classification of ecosystems and derivation of species richness and endemism datasets**
2. **Climate change anomalies: derivation of anomaly datasets for precipitation and temperature**
3. **Climate change severity: development and derivation of a Climate Change Severity Index (CCSI)**
4. **Critical habitats: integration of the climate change severity index with ecosystem and species datasets for identification of critical areas for biodiversity**

Stages one and two only involved aggregation and simple analysis of various data, whereas in stages three and four we have developed new methods and measures to analyze potential impacts of climate change on biodiversity. Therefore, we include the maps of biodiversity and climate change anomalies within this **Methodology** section, and we save the CCSI as well as the critical habitats for the **Results**, because they involve an integration of various factors.

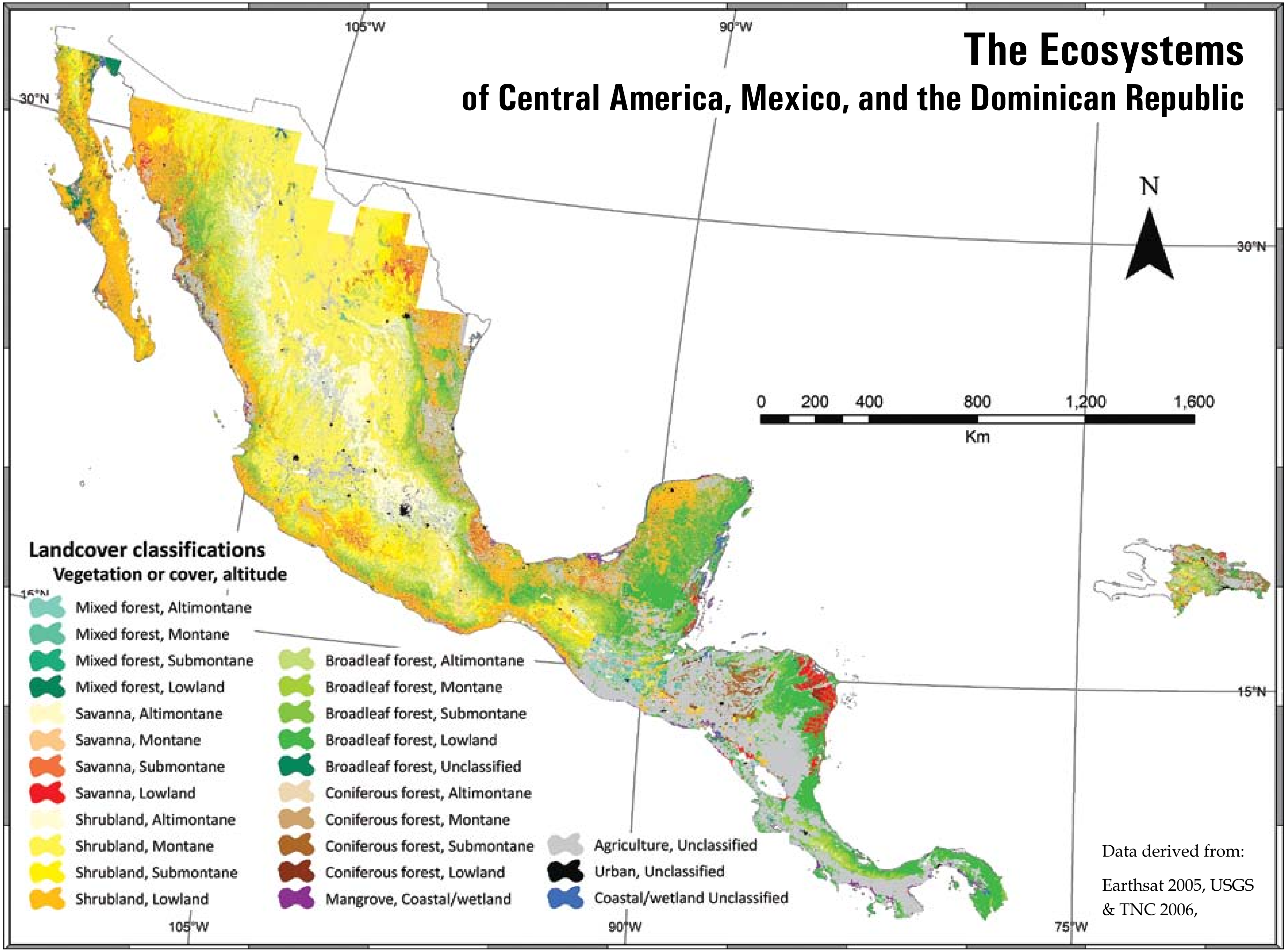
The type of modeling employed in this study required that all input datasets exist in a geospatial format. As such, the lack of georeferenced data on aquatic or marine biodiversity and the lack of downscaled outputs for the oceans (e.g. sea temperature at multiple depths, pH, salinity) precluded investigation of the impacts of climate change on aquatic and marine biodiversity. This study therefore focuses on the potential impacts of climate change on terrestrial biodiversity.

1. Biodiversity

This study addresses two levels of biodiversity: ecosystems and species. We start with ecosystems, since they are the environment in which species live. In the following, we will provide biodiversity maps at a regional level, followed by a suggested manner to monitor important species.

Ecosystems

The data in this analysis come from the Central American Ecosystem Mapping project, which was published in 2002. The project identified a very rich list of 197 ecosystems in the Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama. In order to have a common classification scheme in Mexico and the Dominican Republic, we apply a similar classification scheme to the two countries. The ability to distinguish between land covered by natural vegetation and other land covers is extremely useful in the development of protected areas networks and biological corridors. We separate broadleaf forest, coniferous forest, mixed forest, savanna, and shrubland, into four distinct classifications based on elevation. We then divide elevation into lowland, submontane, montane, and altimontane, where the actual values depend upon an ecosystem's location on the Pacific or Atlantic slope. These inputs result in a layer of over twenty different types of ecosystems, based on vegetation type and land cover and altitude.



The Ecosystems

of Central America, Mexico, and the Dominican Republic

Data derived from:

Earthsat 2005, USGS & TNC 2006,

Species Richness

The number of unique species in a place is known as species richness. Here we divide species richness into three classes—birds, mammals, and amphibians. In order to obtain this type of biodiversity map, we have overlain thousands of species habitat range maps, otherwise known as distribution data. The InfoNatura database developed by NatureServe provided the relevant species distribution data. This compilation of spatial data is the result of aggregating information about all of the documented birds, mammals, and amphibians of Latin America. Two advantages of this system are that it has harmonized disparate types of data into a common format, and it also includes information from multiple reputable sources.

By overlaying the distribution data for each bird species, each mammal species, and each amphibian species, we obtained richness maps for the entire region. A simplified illustration of this process is shown

Adding the three classes together results in our fundamental measure of animal biodiversity—species richness.

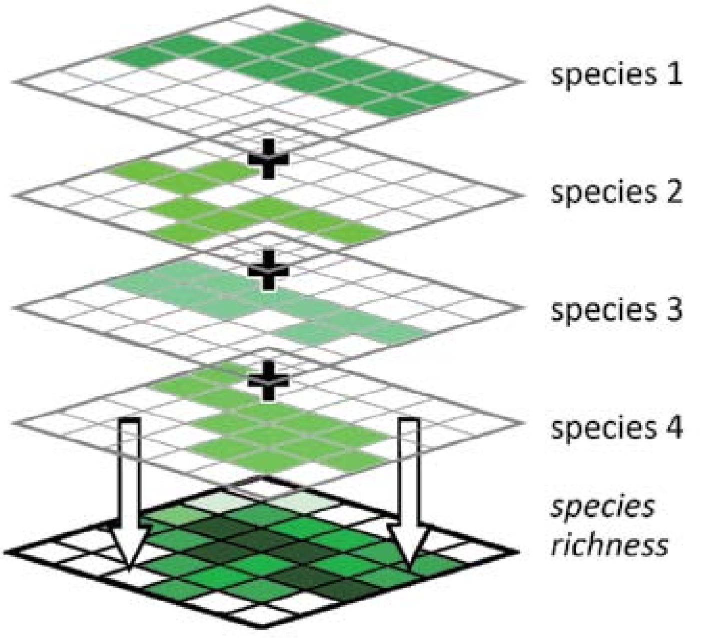
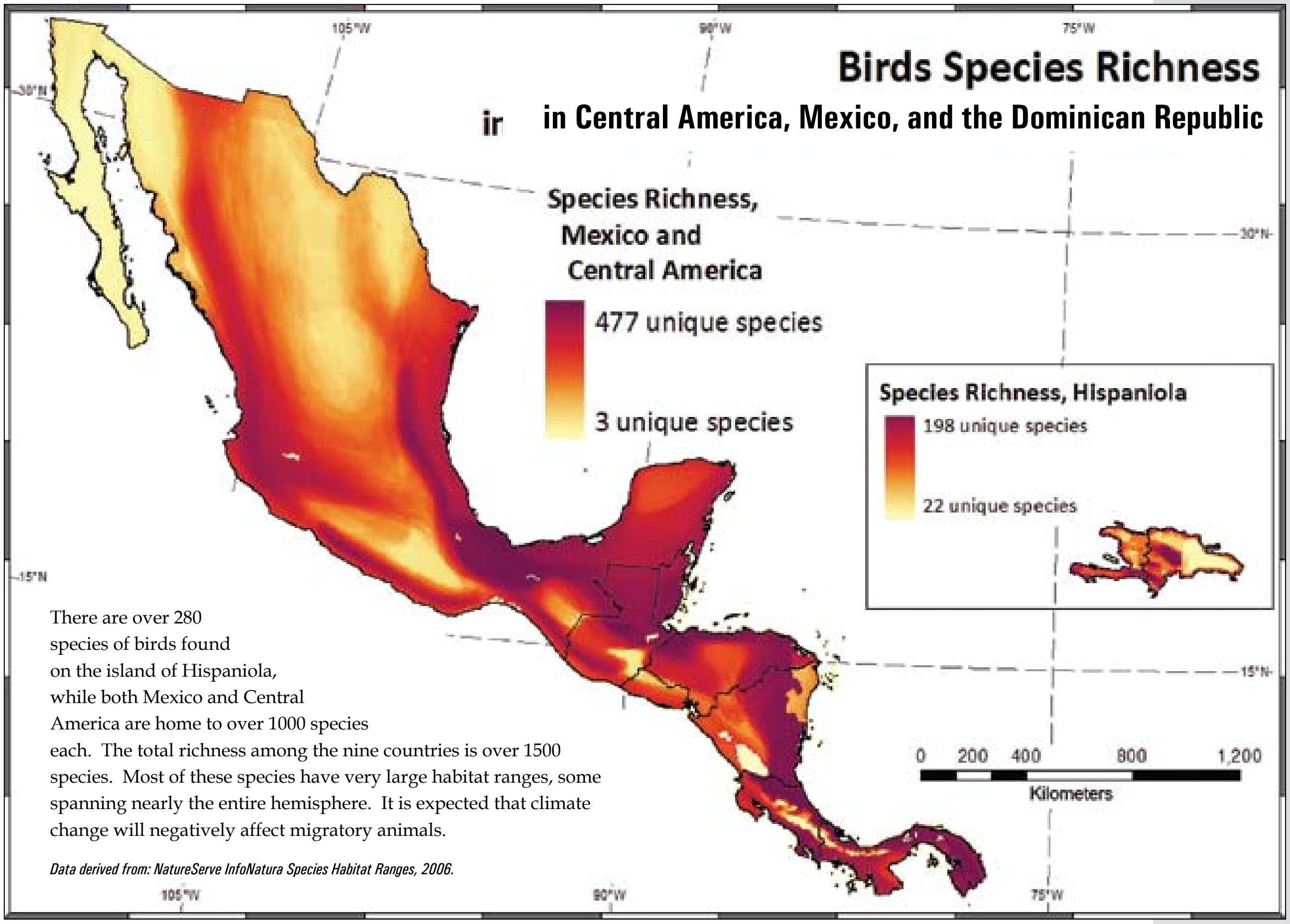


Figure 5 *Adding individual species habitat ranges to calculate species richness. Darker green indicates higher richness because more species inhabit that area.*

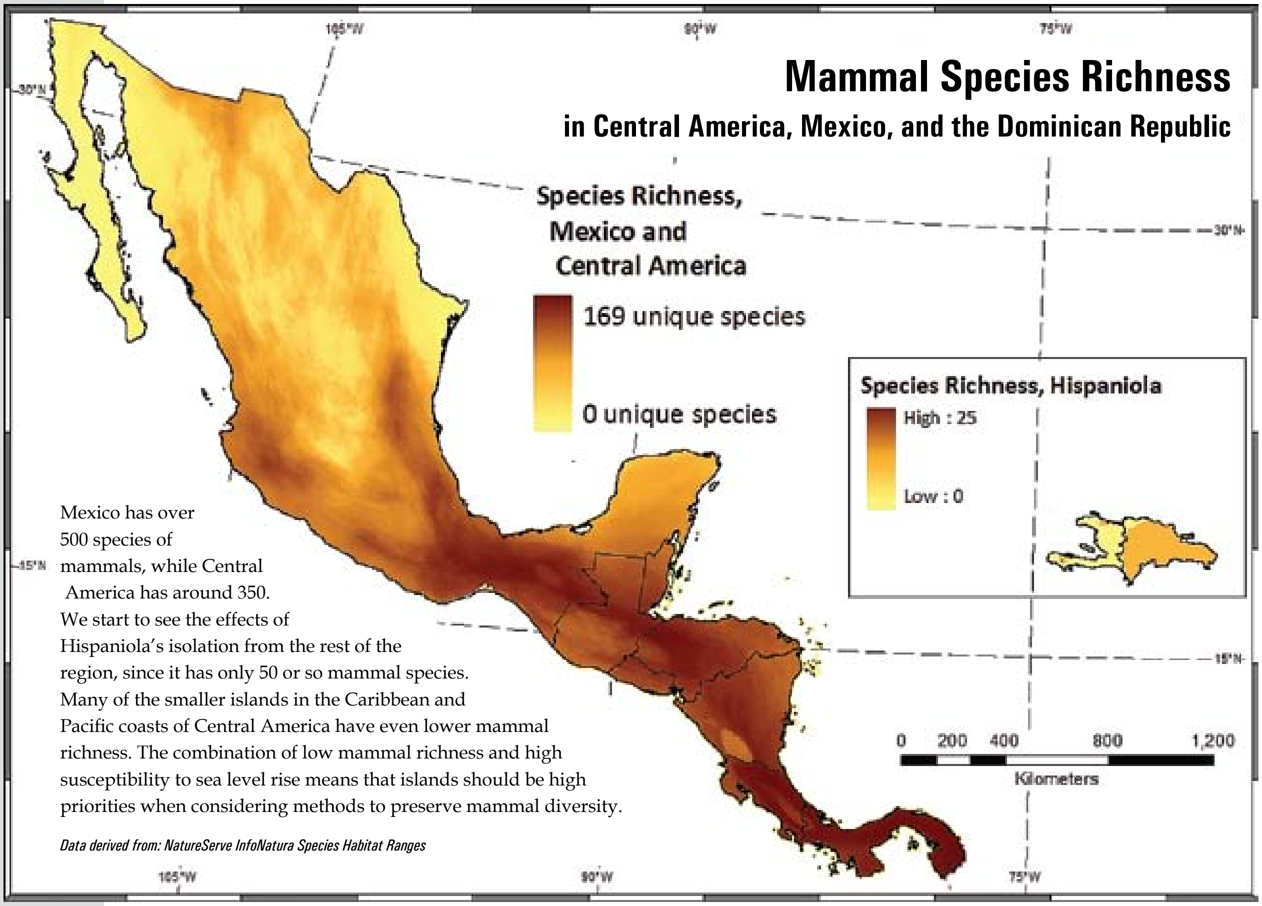


There are over 280 species of birds found on the island of Hispaniola, while both Mexico and Central America are home to over 1000 species each. The total richness among the nine countries is over 1500 species. Most of these species have very large habitat ranges, some spanning nearly the entire hemisphere. It is expected that climate change will negatively affect migratory animals.

Data derived from: NatureServe InfoNatura Species Habitat Ranges, 2006.

Mammal Species Richness

in Central America, Mexico, and the Dominican Republic

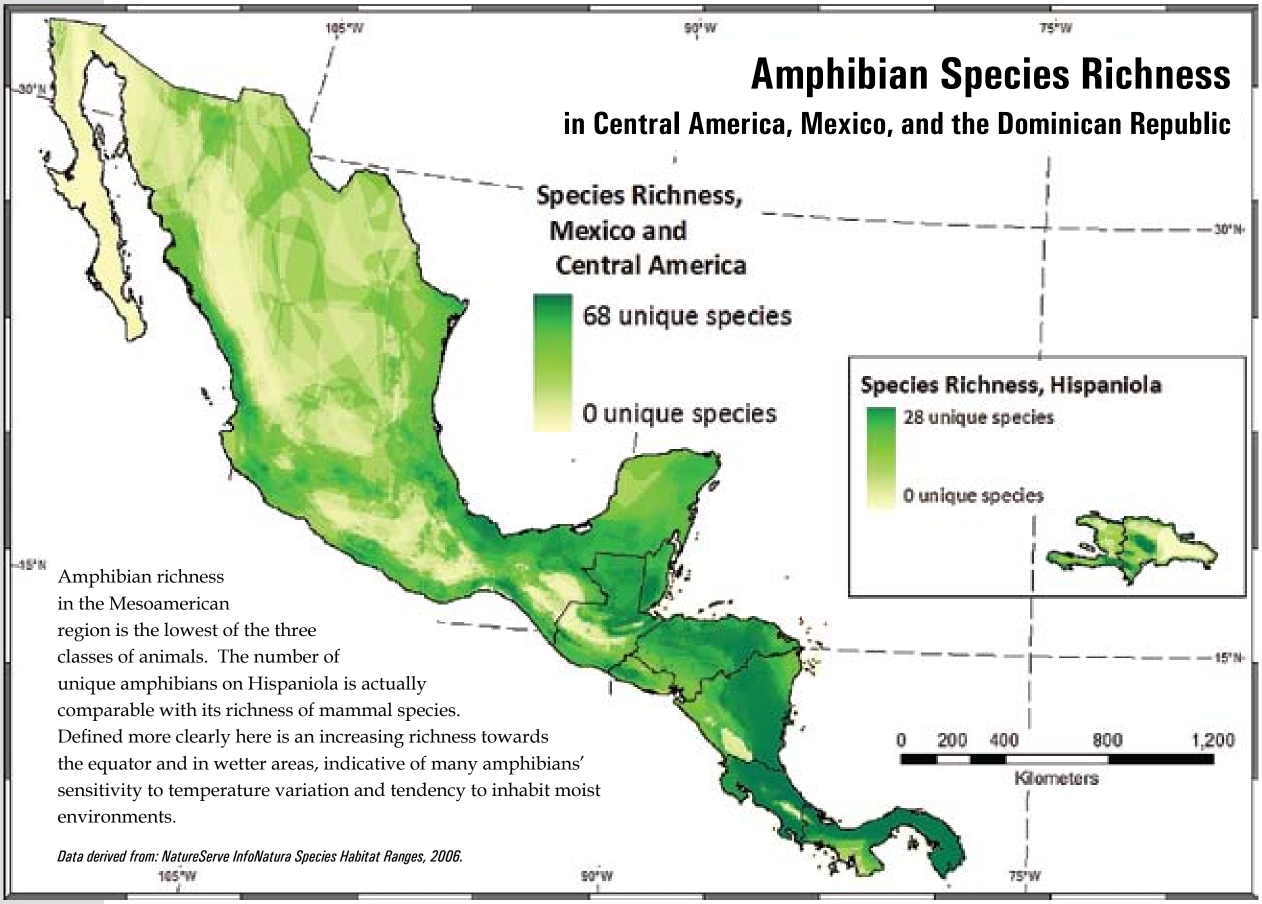


Mexico has over 500 species of mammals, while Central America has around 350. We start to see the effects of Hispaniola's isolation from the rest of the region, since it has only 50 or so mammal species. Many of the smaller islands in the Caribbean and Pacific coasts of Central America have even lower mammal richness. The combination of low mammal richness and high susceptibility to sea level rise means that islands should be high priorities when considering methods to preserve mammal diversity.

Data derived from: NatureServe InfoNatura Species Habitat Ranges

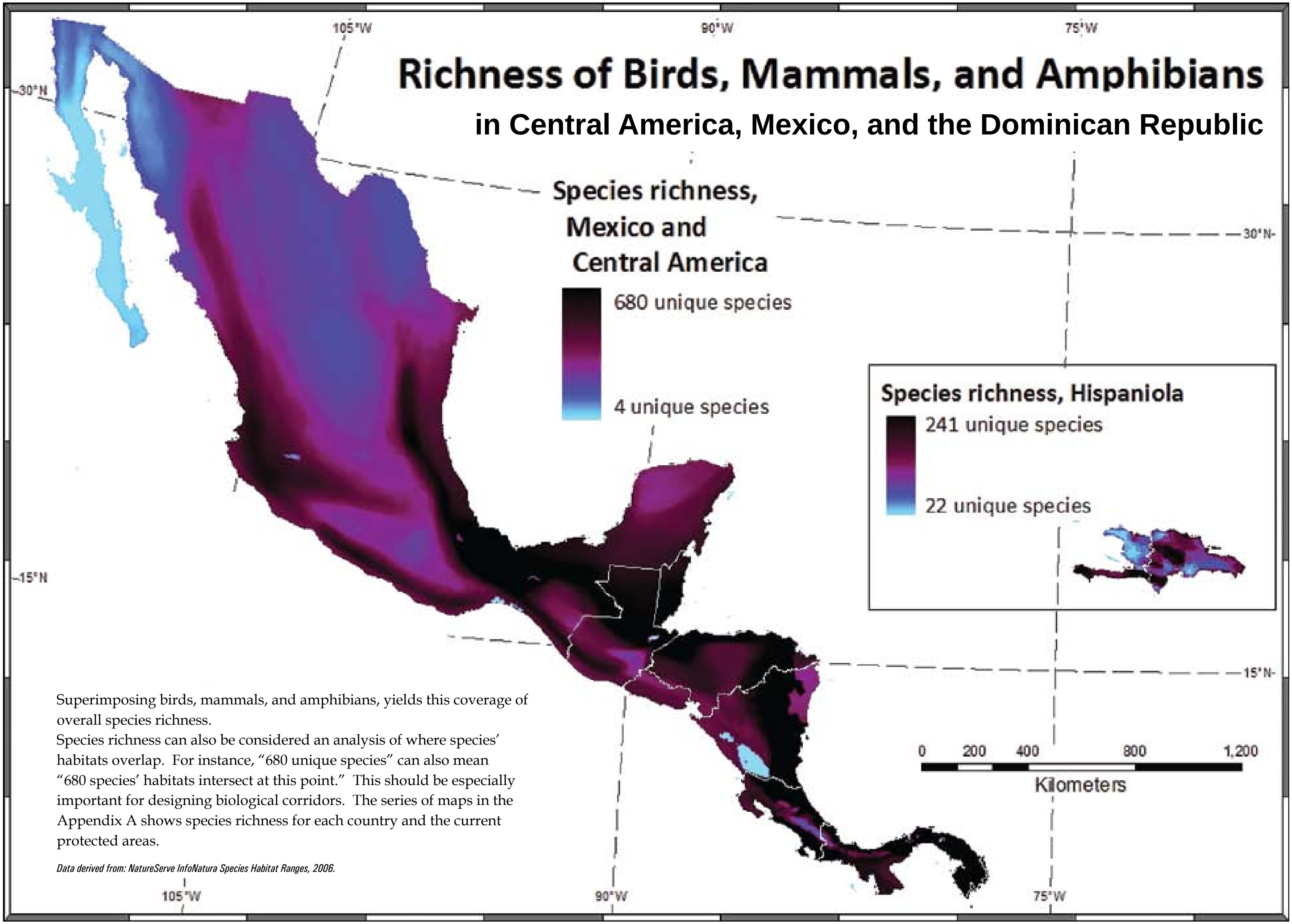
Amphibian Species Richness

in Central America, Mexico, and the Dominican Republic



Amphibian richness in the Mesoamerican region is the lowest of the three classes of animals. The number of unique amphibians on Hispaniola is actually comparable with its richness of mammal species. Defined more clearly here is an increasing richness towards the equator and in wetter areas, indicative of many amphibians' sensitivity to temperature variation and tendency to inhabit moist environments.

Data derived from: NatureServe InfoNatura Species Habitat Ranges, 2006.



Richness of Birds, Mammals, and Amphibians
in Central America, Mexico, and the Dominican Republic

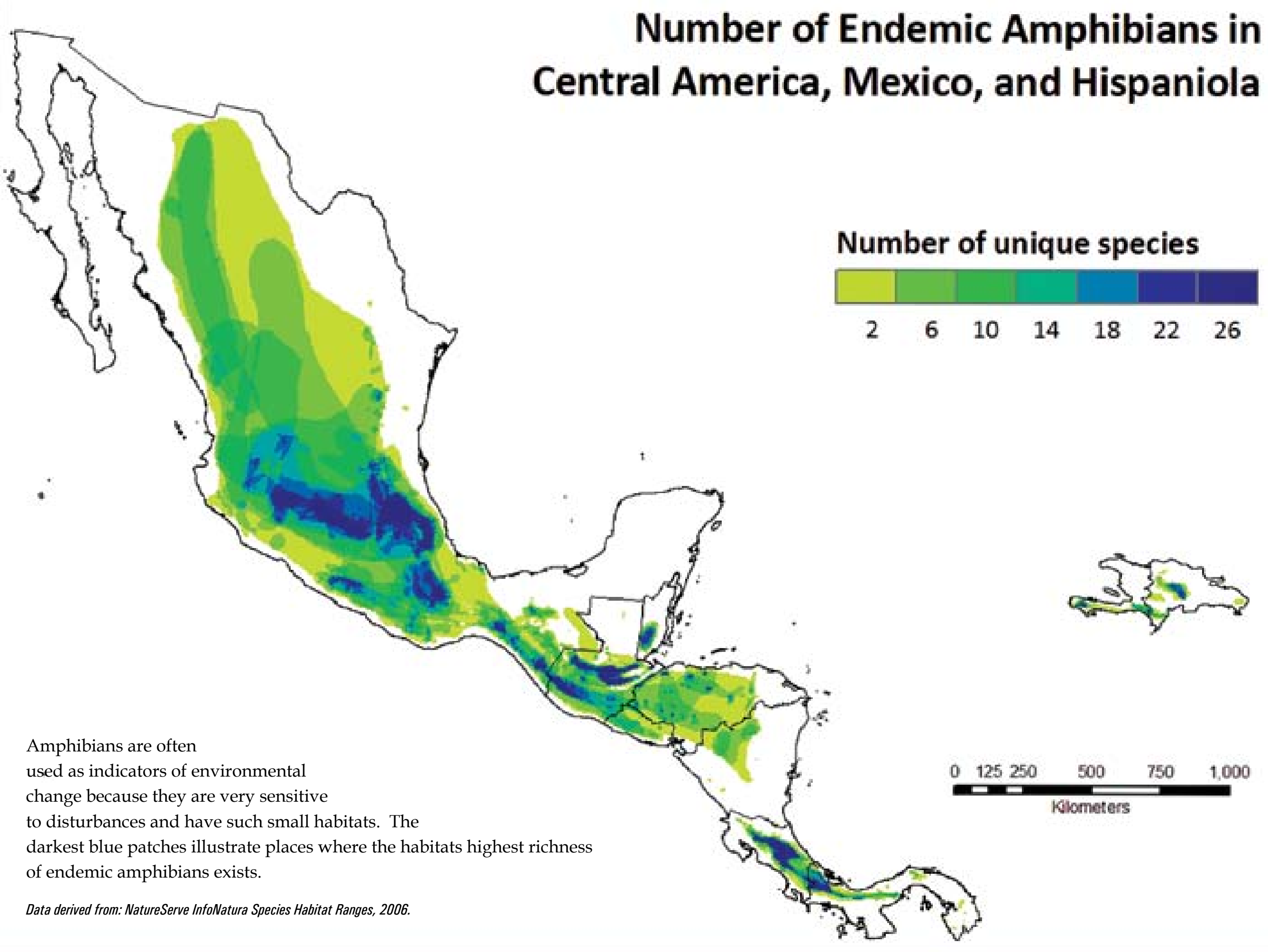
Superimposing birds, mammals, and amphibians, yields this coverage of overall species richness.
Species richness can also be considered an analysis of where species' habitats overlap. For instance, "680 unique species" can also mean "680 species' habitats intersect at this point." This should be especially important for designing biological corridors. The series of maps in the Appendix A shows species richness for each country and the current protected areas.

Data derived from: NatureServe InfoNatura Species Habitat Ranges, 2006.

Endemic Species

Another popular measurement of biodiversity is that of endemic species. These species live in a certain area or areas, and nowhere else; therefore, these species usually have the smallest distribution ranges. Moreover, endemic species are very susceptible to changes in climate because their spatial mobility is more limited than species with large habitat ranges.

Endemic species are sometimes considered to be indicator species, too. Indicator species are usually the most sensitive to perturbations, and drastic changes in their population almost always raise a flag. Endemic amphibians are often monitored as indicators because of their high sensitivity to environmental degradation and small habitat ranges.


Number of Endemic Amphibians in Central America, Mexico, and Hispaniola

Amphibians are often used as indicators of environmental change because they are very sensitive to disturbances and have such small habitats. The darkest blue patches illustrate places where the habitats highest richness of endemic amphibians exists.

Data derived from: NatureServe InfoNatura Species Habitat Ranges, 2006.

2. Climate Change Anomalies

As mentioned before, developing such a wide array of global climate models is an impressive achievement and is very useful for large-scale studies. Unfortunately, they cannot capture regional and local phenomena, which are important to many ecologists, botanists, and zoologists, because the spatial resolution of global climate models is so coarse. Thus, methods have been developed to obtain finer results: regional downscaling. Regional climate models provide higher resolution results, which demonstrate local climatic effects (Figure 11). In this sense, they are much more useful for local and regional climate impact assessments, particularly on biodiversity.

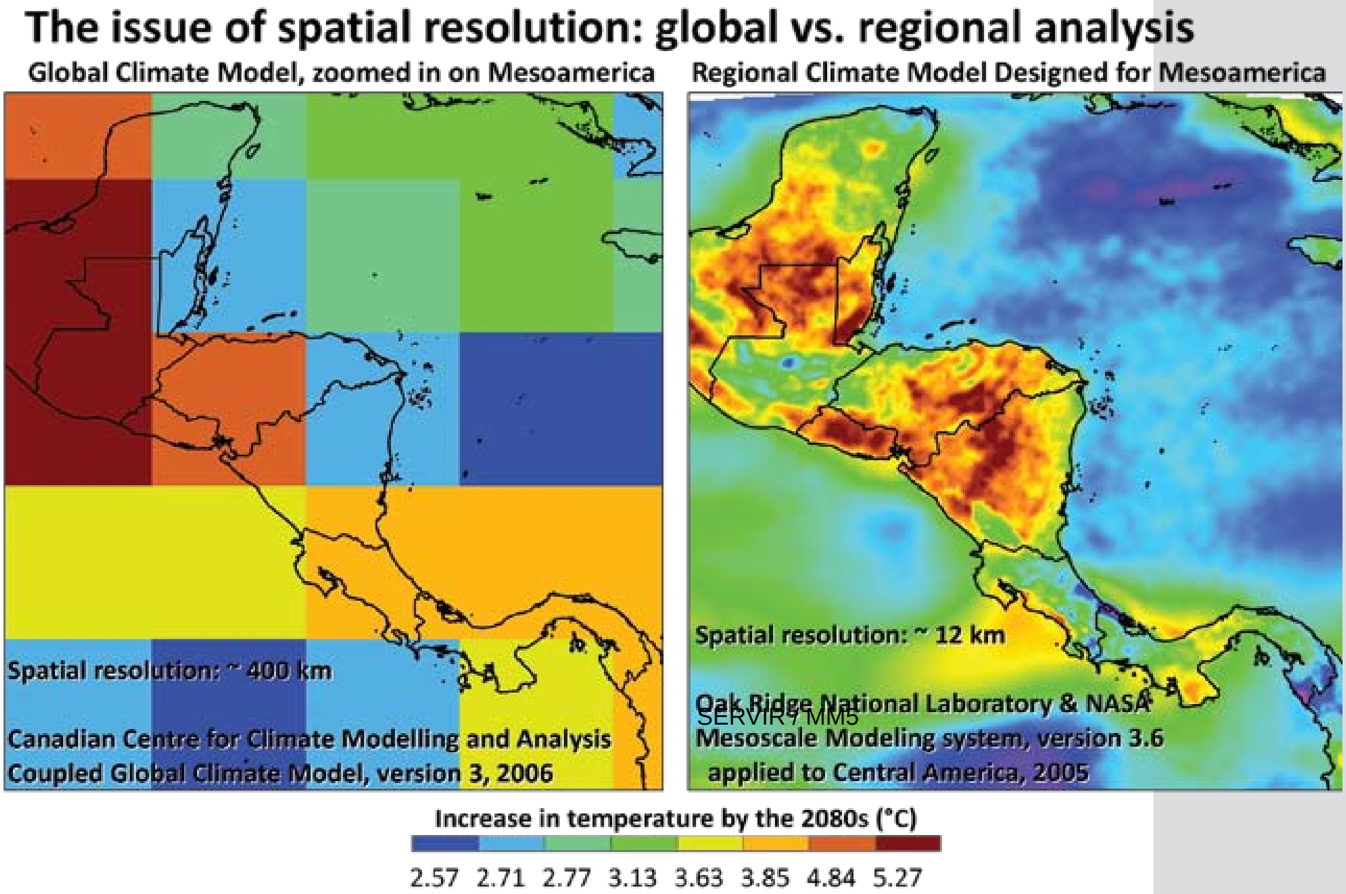


Figure 11 This case of Central America demonstrates the difference in spatial resolution between a global climate scenario and a regional climate scenario.

Both cases above involved coupled models and required immense computational resources. The Coupled Global Climate Model was designed and tuned to most accurately display global trends, while the Mesoscale Modeling custom-designed a regional downscaling for Central America. The second did not generate its own global climate data; rather, it used existing global data to feed into a regional model. It is evident that the local climatic effects have been captured in the second model (Hernandez et al. 2006).

The necessity of higher resolution climate scenarios for applications to biodiversity has already been demonstrated in numerous investigations. Scientists have underlined climate change's role in driving several species to near extinction. For instance, the Central American harlequin frogs and Panamanian golden frogs of the region's cloud forests have been victim of a disease caused by certain types of fungus (Pounds 2006). Recently, climate changes in these areas have created more favorable conditions for the expansion of this fungus, hence placing these rare frogs under even more pressure. Models that demonstrate the intricacies of possible climate changes in particular localities will support studies involving species with such small habitat ranges, and perhaps such knowledge will better guide our strategies of adaptation to climate change.

While there are endless ways to display and assess climate change scenarios, we include a selection of the most significant and useful measurements of climate change:

Anomaly section:

- Annual mean temperature anomaly
- Annual precipitation percent change

Severity section:

- Temperature change severity
- Precipitation change severity
- Climate Change Severity Index (CCSI)

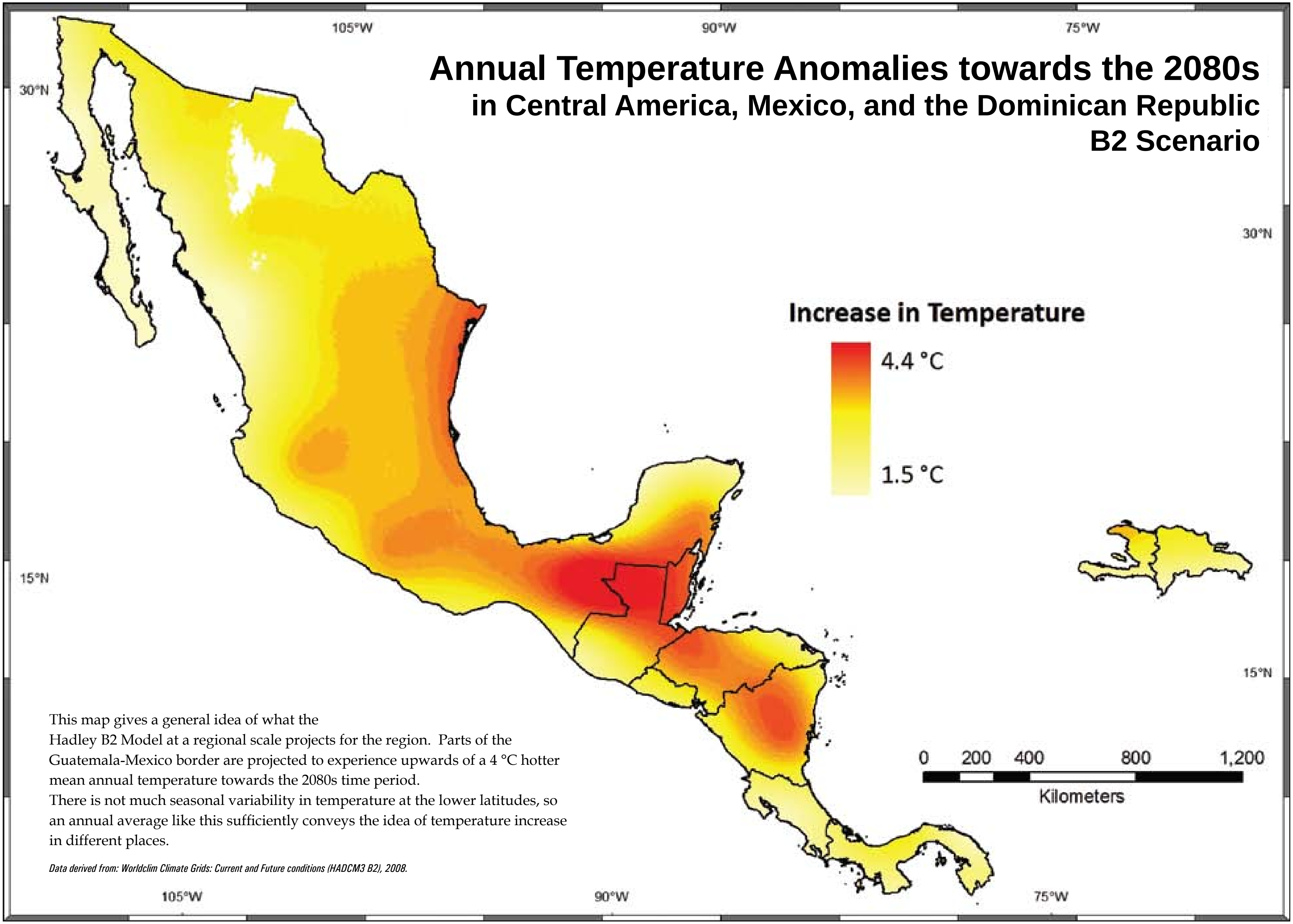
We will first explain the methodology in displaying the anomalies and then display the maps. The concept of anomalies is not by any means a new concept, but we are eager to present our results which were derived from such high resolution regional downscaling. Next, we will describe the inputs and processes for developing the climate change severity index, followed by a series of maps illustrating the results.

Temperature & Precipitation Anomalies

The following section includes larger-scale regional analyses of temperature and precipitation anomalies derived from high resolution regional climate scenario data. While there are endless ways to display and assess climate change scenarios, a common structure is to observe overall tendencies, rather than to make comparisons simply between "today" and a certain date in the future. In other words, there are decades of historical data, just as there are decades worth of future projections. The historical data is commonly called the baseline, which is an average of thirty years usually between 1961 and 1990. Because the climate varies so greatly year to year, choosing to analyze differences based off of one historical year will result in an inadequate description of the greater tendency. By averaging over thirty years in the past, abnormal weather events have been smoothed over, so that we start with truly representative datasets of our current conditions. The same goes for climate change scenarios. Since the models were built to demonstrate climate variability that we experience within and between decades, it is unreasonable to choose only one month or one year of a model output. Doing this would subject your analysis to highly random variation because your input is not representative of the bigger picture. To avoid this, climate scenario data is also summarized like baseline data. The most common way to group future projections is by the "2020s," the "2050s," and the "2080s." Like the baseline data, these future time periods include an average of thirty years. For example, the 2020s are an average of all the years from 2011 to 2040. The 2050s include 2041 through 2060, and the 2080s include 2061 through 2090.

Given these considerations, we choose to display the temperature anomaly as a difference between projections for the 2080s and the baseline. Using the downscaled Hadley Center's global climate model, B2 and A2 scenarios, we will see temperature anomalies for one of the better-case scenarios and worst case scenarios, respectively. In an appendix of country profiles (Appendix A), we display maps of temperature anomalies toward the 2020s and 2080s.

Because annual precipitation varies so greatly within the countries of interest, we calculate the percent change in annual accumulation of precipitation between the 2020s and the baseline, rather than the raw difference, for the B2 and A2 scenarios. This gives a better idea of how precipitation is projected to change, keeping in mind an area's normal accumulation. Also, because there are more disagreements among the various climate change scenarios in terms of precipitation changes, we do not display projections towards the 2080s. These deviations are evident in Appendix A. A general trend among all of the climate change scenarios is that there is a projected drying of the wet season. Because of this, we choose to include in Appendix A the percent change of accumulated precipitation during July, August, and September.

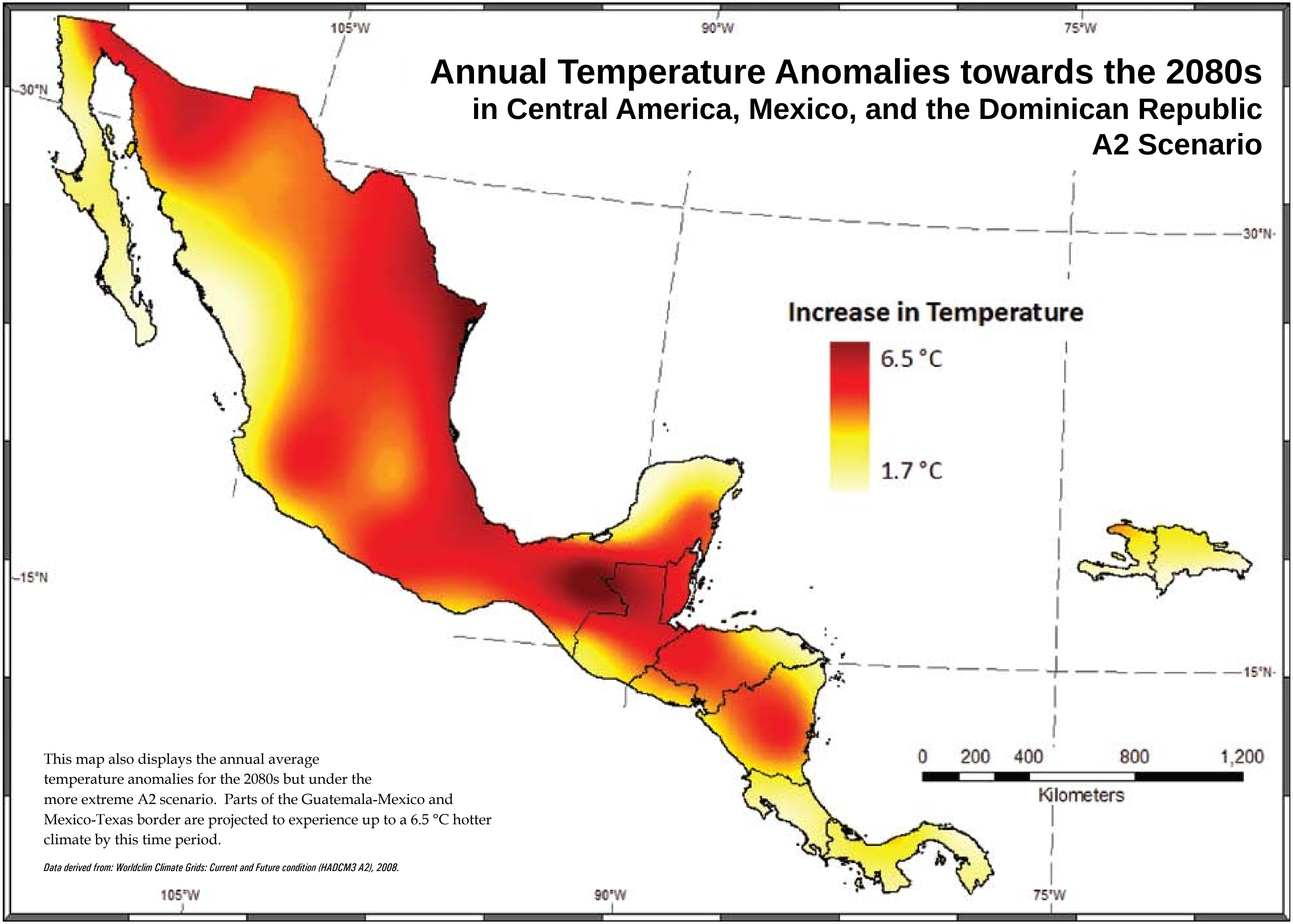


Annual Temperature Anomalies towards the 2080s
in Central America, Mexico, and the Dominican Republic
B2 Scenario

This map gives a general idea of what the Hadley B2 Model at a regional scale projects for the region. Parts of the Guatemala-Mexico border are projected to experience upwards of a 4 °C hotter mean annual temperature towards the 2080s time period.
There is not much seasonal variability in temperature at the lower latitudes, so an annual average like this sufficiently conveys the idea of temperature increase in different places.

Data derived from: Worldclim Climate Grids: Current and Future conditions (HADCM3 B2), 2008.

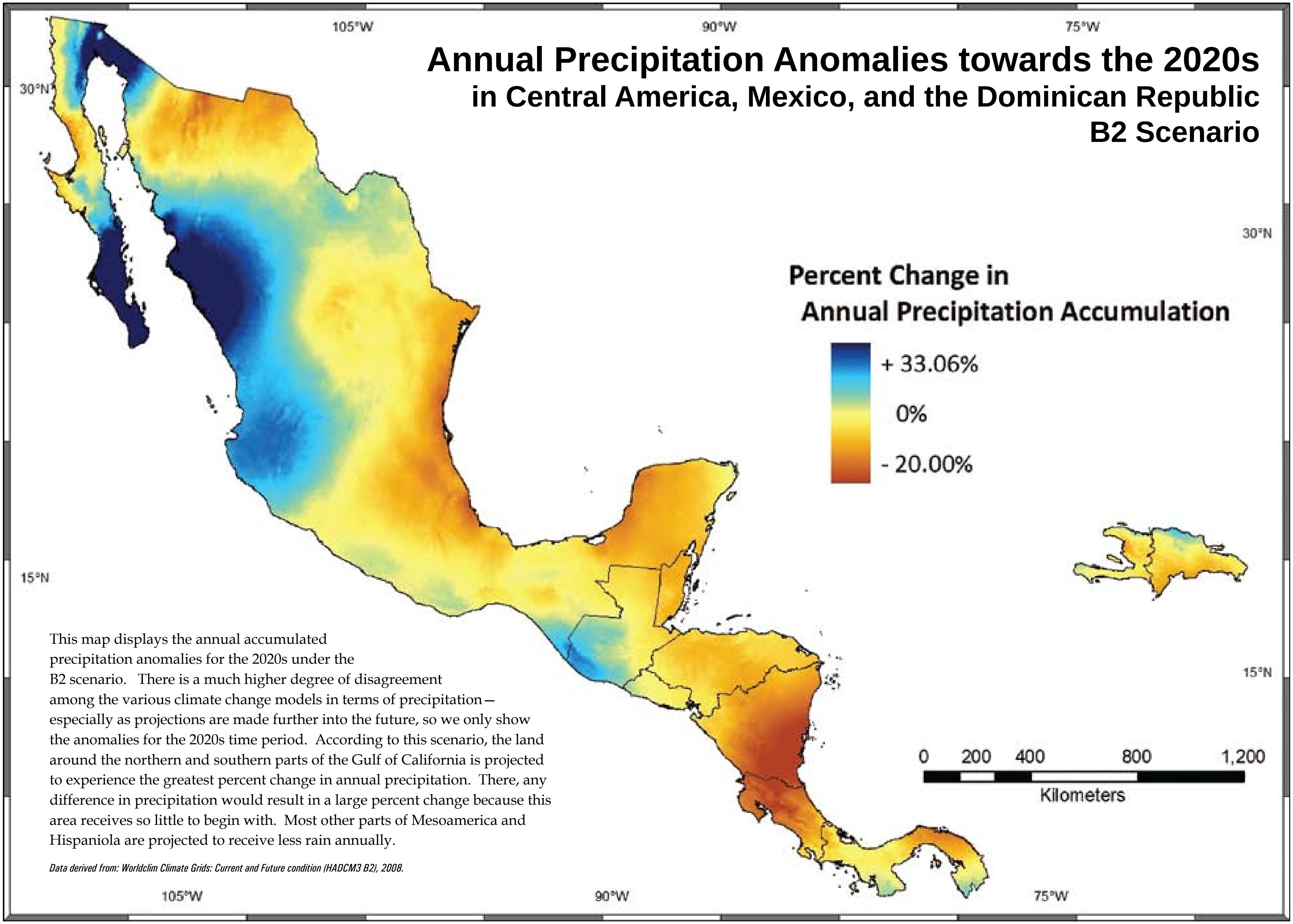
Annual Temperature Anomalies towards the 2080s
in Central America, Mexico, and the Dominican Republic
A2 Scenario



This map also displays the annual average temperature anomalies for the 2080s but under the more extreme A2 scenario. Parts of the Guatemala-Mexico and Mexico-Texas border are projected to experience up to a 6.5 °C hotter climate by this time period.

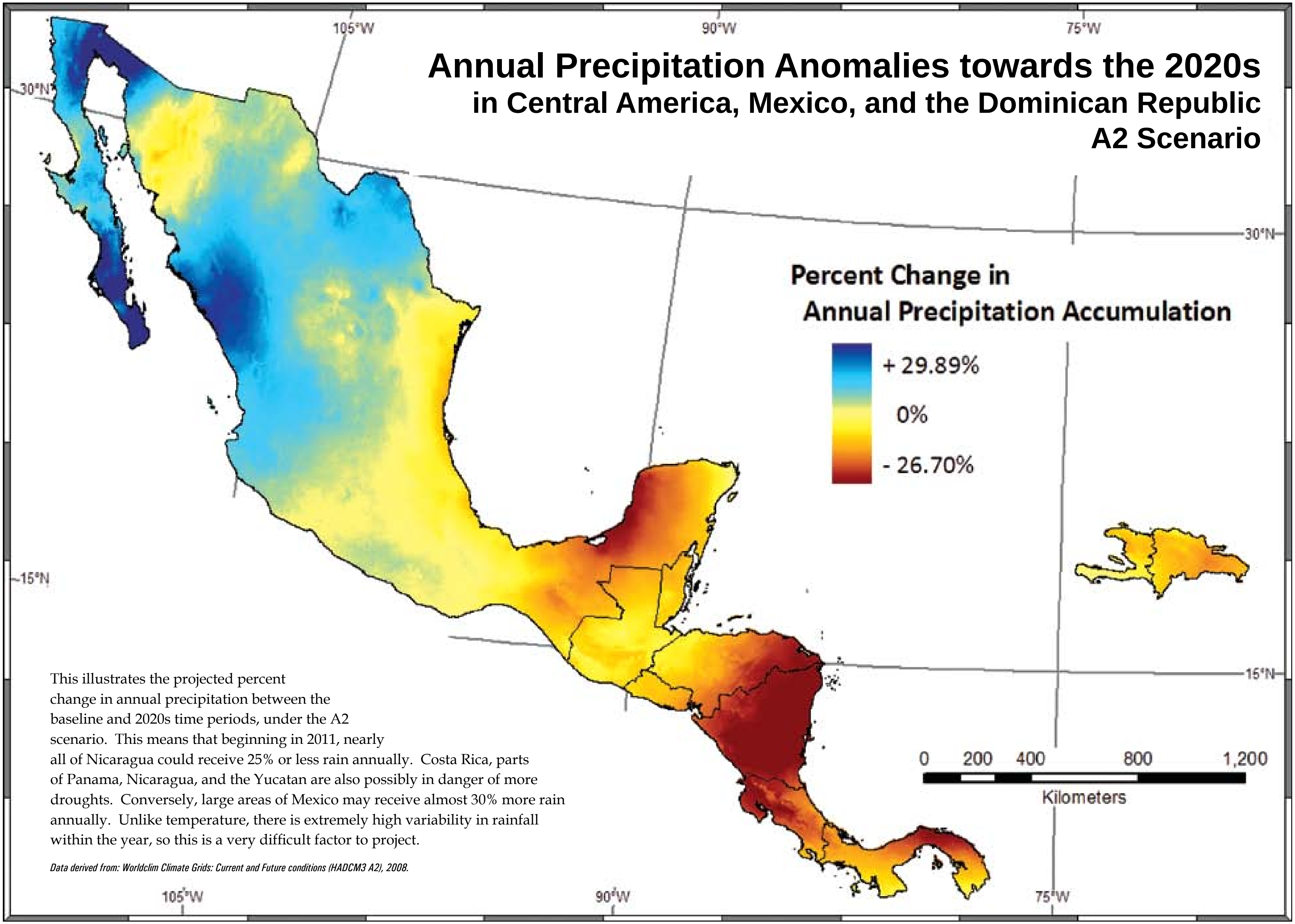
Data derived from: Worldclim Climate Grids: Current and Future condition (HADCM3 A2), 2008.

Annual Precipitation Anomalies towards the 2020s
in Central America, Mexico, and the Dominican Republic
B2 Scenario



This map displays the annual accumulated precipitation anomalies for the 2020s under the B2 scenario. There is a much higher degree of disagreement among the various climate change models in terms of precipitation—especially as projections are made further into the future, so we only show the anomalies for the 2020s time period. According to this scenario, the land around the northern and southern parts of the Gulf of California is projected to experience the greatest percent change in annual precipitation. There, any difference in precipitation would result in a large percent change because this area receives so little to begin with. Most other parts of Mesoamerica and Hispaniola are projected to receive less rain annually.

Data derived from: Worldclim Climate Grids: Current and Future condition (HADCM3 B2), 2008.



Annual Precipitation Anomalies towards the 2020s
in Central America, Mexico, and the Dominican Republic
A2 Scenario

This illustrates the projected percent change in annual precipitation between the baseline and 2020s time periods, under the A2 scenario. This means that beginning in 2011, nearly all of Nicaragua could receive 25% or less rain annually. Costa Rica, parts of Panama, Nicaragua, and the Yucatan are also possibly in danger of more droughts. Conversely, large areas of Mexico may receive almost 30% more rain annually. Unlike temperature, there is extremely high variability in rainfall within the year, so this is a very difficult factor to project.

Data derived from: Worldclim Climate Grids: Current and Future conditions (HADCM3 A2), 2008.

3. Climate Change Severity

Building off of the framework of the EVCC index that had been prototyped by Tremblay-Boyer and Anderson (2007), a Climate Change Severity Index (CCSI) was constructed utilizing baseline climate data and derived monthly anomaly data. The CCSI was itself derived from respective a Temperature Change Severity Index and a Precipitation Change Severity Index that were derived. These were derived as follows:

Temperature Change Severity Index (CCSIt):

$$\frac{|\text{ Annual mean scenario temperature} - \text{Annual mean baseline temperature }|}{\text{Baseline temperature range}}$$

Precipitation Change Severity Index (CCSIp):

$$\frac{|\text{ Annual scenario precipitation accumulation} - \text{Annual baseline precipitation accumulation }|}{\text{Baseline precipitation accumulation range}}$$

Climate Change Severity Index (CCSI):

$$\frac{CCSI_t + CCSI_p}{2}$$

Table of expected CCSI values, given individual $CCSI_t$ and $CCSI_p$

		Precipitation ($CCSI_p$)	
		Low $CCSI_p$	High $CCSI_p$
Temperature ($CCSI_t$)	Low $CCSI_t$	Low severity	Depends on combination
	High $CCSI_t$	Depends on combination	High severity

The CCSI therefore measures the climate change that a particular location may undergo, compared to the natural climate variation[1] that a location has experienced historically (i.e. its current 'comfort zone'[2]). In other words, the CCSI is a measure of how far a location will be placed outside of its current climate comfort zone. In terms of location, the CCSI can be derived at a range of spatial scales, depending on the spatial resolution or detail of the available climate data.[3] Derivation of the CCSI yields raw quantitative values which are interpreted as follows:

Table 1: Range and Significance of CCSI Values

Values	Severity
0 – 0.24	Low severity
0.25 – 0.49	Approaching significant changes
0.50 – 0.74	Significant changes vary during year
0.75 – 0.99	Pushing comfort zone limits
1.00 – 1.99	Outside comfort zone
2.00+	Far outside comfort zone

Specifically within this study, we derive the CCSI using the WorldClim data, which at 1km2 spatial resolution constitute the highest spatial resolution inputs currently available. We derive the CCSI for the range of scenarios and models available from WorldClim, specifically CGCM3, CSIRO MK3, and HADCM3, with respect to both worst case (A2) and better case (B2) scenarios. While information for the range of scenarios was analyzed, the results present a focus on the A2 and B2 scenarios of the HADCM3 data, which represented, for the most part, the most extreme and a less extreme of the climate scenarios, respectively.[4]

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[1] With regard to the CCSI, this is reflected particularly in terms of the precipitation and temperature regimes that impact said location.

[2] While we refer to this by the term 'comfort zone' repeatedly throughout this document, this is most often reflected in the scientific literature as 'climatic space.'

[3] That is, the CCSI can be derived from the low resolution GCM data, or using higher-resolution downscaled data such as those available from PRECIS, SERVIR or WorldClim.

[4] For specific information on how the various scenarios available through WorldClim differed, please refer to Appendix A.

RESULTS

Here, we explore the implications of the modeling; however, because of the uncertainties that are associated, overall, with downscaled climate scenario data, these results must nonetheless be treated with the proverbial 'grain of salt.'

The following series of maps display the Temperature Change Severity Index and Precipitation Change Severity Index for the 2020s and 2080s. We also show the Climate Change Severity Index for the 2020s. Since precipitation deviates greatly into the 2080s among the different climate change models, we project the severity of climate change only for the 2020s and the 2050s. For more complete results, we an Appendix C all of the CCSI maps (three modeling organizations x two scenarios x three time periods = eighteen maps). This should provide the reader with a visualization of how we project climate change severity to increase in time as well as an understanding of the variability among scenarios and models.

Overall trends

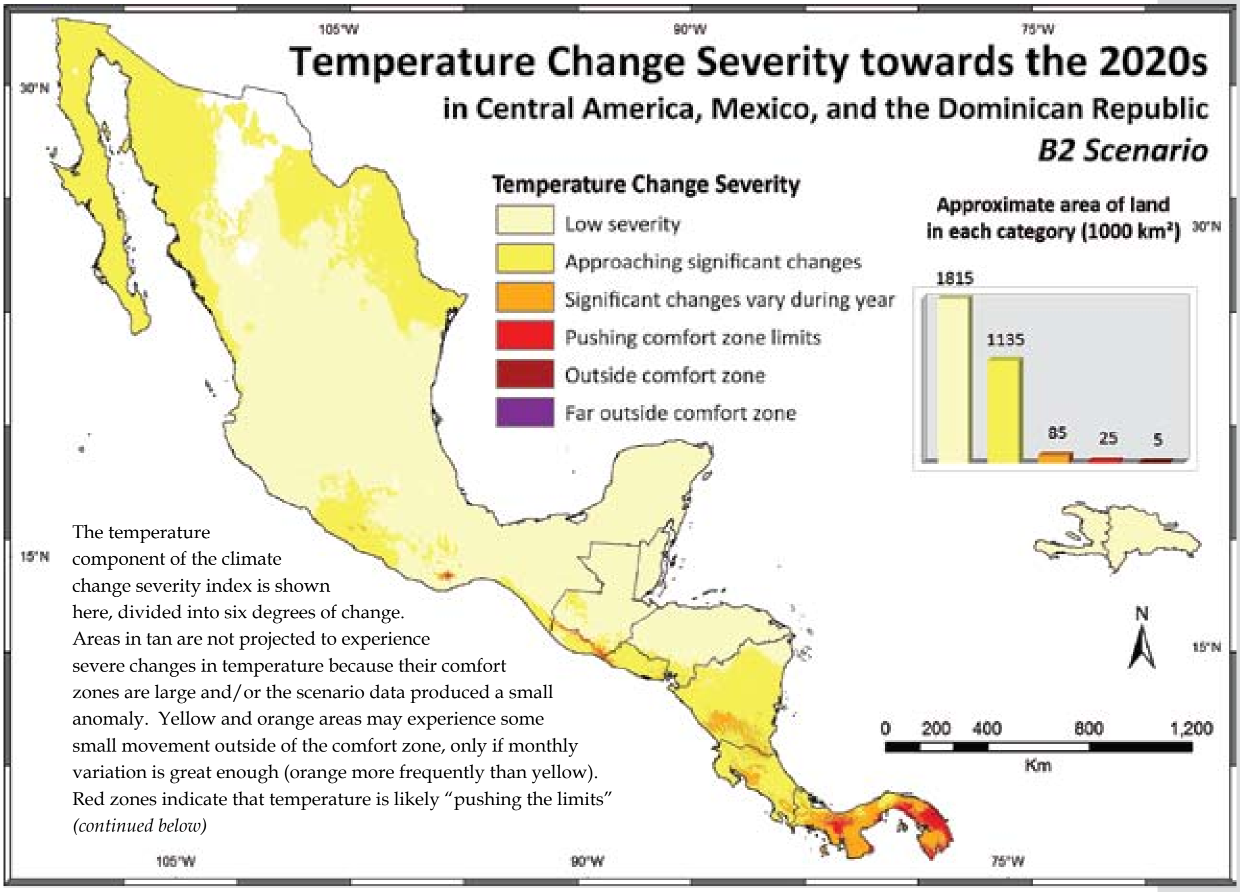
Despite the existing uncertainties, almost all of the various climate change models agree on projected conditions in the nearest time period, the 2020s, regardless of worst or best case scenario. This is why we put more emphasis in analyzing and discussing the 2020s. In terms of overall trends, according to the modeling work conducted, if worst case scenario conditions prevail, in the near-term, the Caribbean coasts of lower Central America will be significantly impacted by climate change. Countries that would be affected include Costa Rica, the Dominican Republic, Honduras, Nicaragua and Panama.

In the 2020s, under the worst case scenario, species and ecosystems across specific sites in Central America and the Dominican Republic would indeed face a significant climatic stresses by being subjected to precipitation and temperature regimes far outside of the natural variation or "comfort zone" to which they have been accustomed.

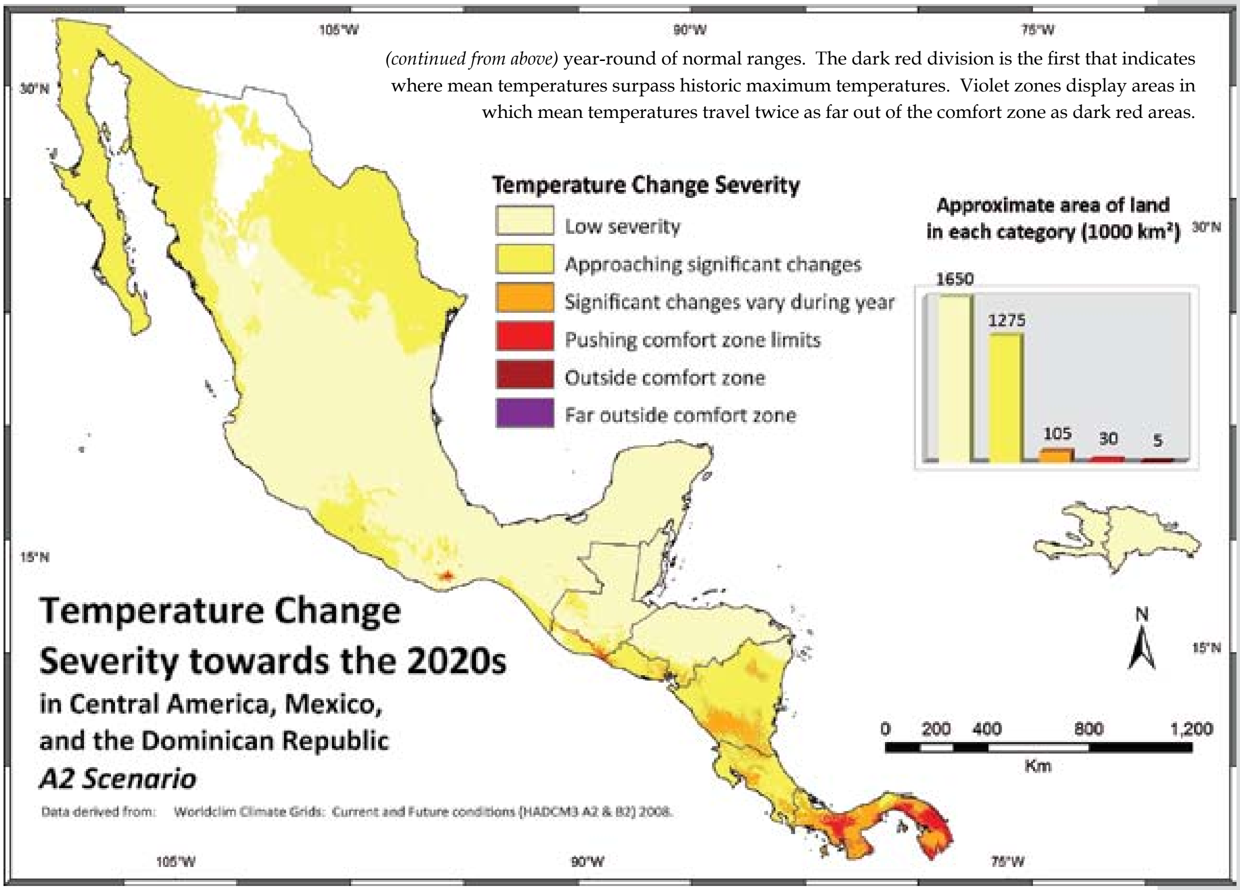
With the exception mainly of parts of Baja California and the Yucatan Peninsula, Mexico's ecosystems and species would go largely unaffected even under worst case scenario conditions. This is because the majority of Mexico's ecosystems already tolerate a relatively wide margin of climate variation, likely indicating resilience to climate change. In fact, irrespective of the climate scenario data, the historic climate data indicates that the vast majority of ecosystems in Central America and the Caribbean are currently exposed to relatively low variation in terms of rainfall patterns and temperature. Overall, the climatic "comfort zones" of species and ecosystems in Central America and the Caribbean are relatively small.

Nevertheless, in terms of this "comfort zone" of climatic niches that species and ecosystems are tolerant to, if worst case scenario conditions prevail, by the 2080s virtually all of the ecosystems and species of Central America and the Dominican Republic will be subjected to conditions well outside of their traditional "comfort zone." While this abrupt shift may imply altitudinal migration of some species or the extirpation of more immotile endemic species, further research is needed to better assess the potential resilience of specific species and ecosystems.

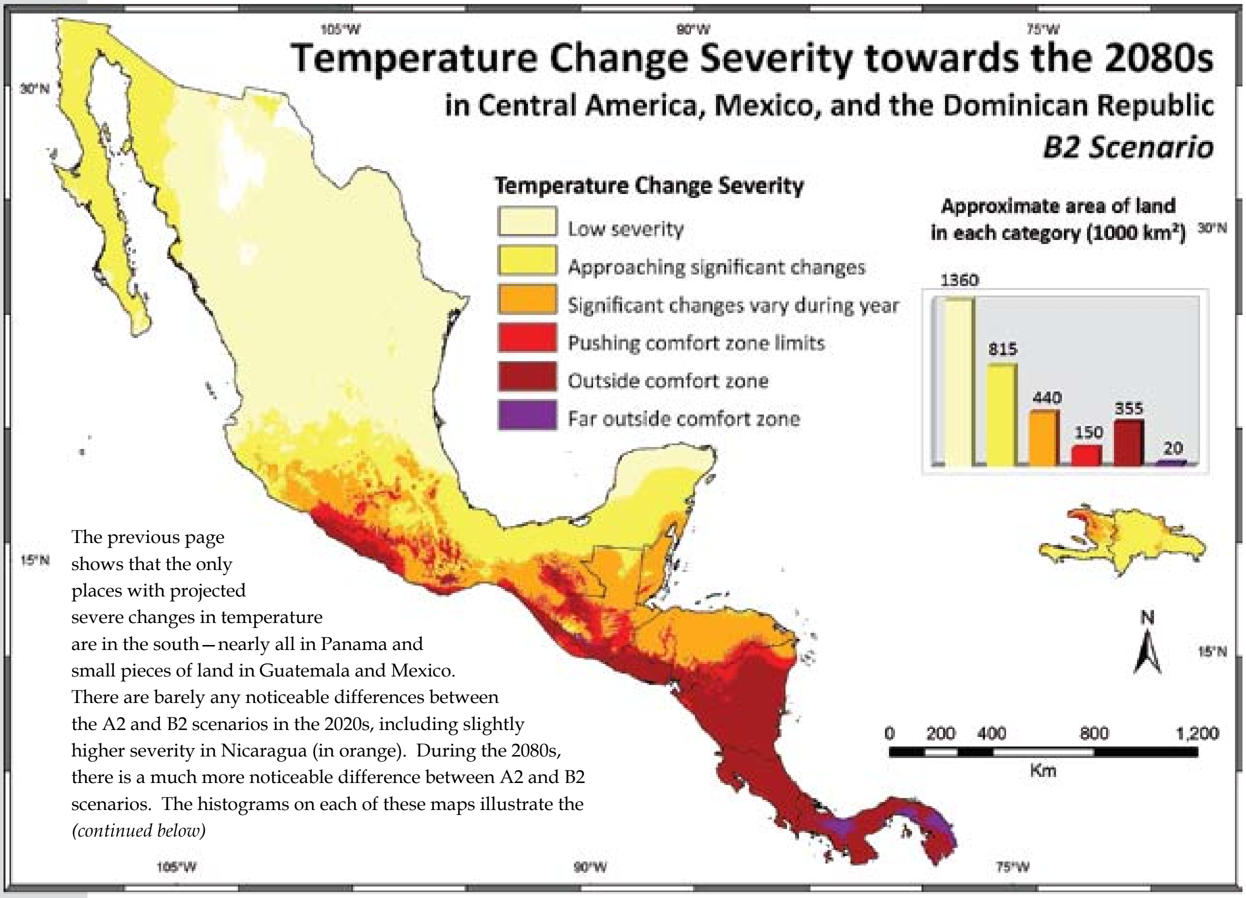
Additionally, in terms of the potential impact on existing protected areas, according to the modeling conducted, the ecosystems and species most likely to be affected by climate change are already within protected areas for a large part. It would therefore expected that if these ecosystems continue to be protected, for a variety of reasons, the chances of these ecosystems adapting to climate change would be higher compared to those vulnerable ecosystems currently outside existing protected areas networks.



The temperature component of the climate change severity index is shown here, divided into six degrees of change. Areas in tan are not projected to experience severe changes in temperature because their comfort zones are large and/or the scenario data produced a small anomaly. Yellow and orange areas may experience some small movement outside of the comfort zone, only if monthly variation is great enough (orange more frequently than yellow). Red zones indicate that temperature is likely "pushing the limits" *(continued below)*

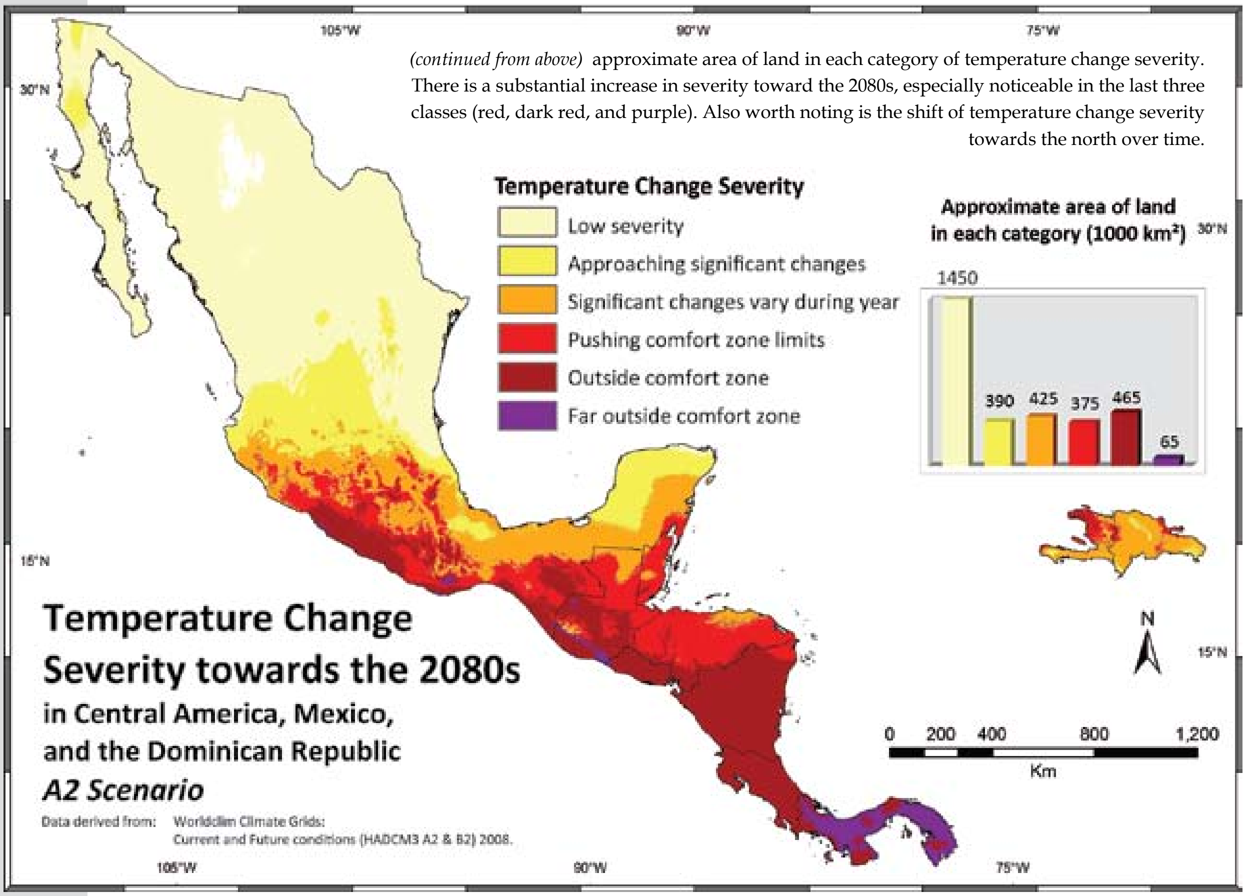


(continued from above) year-round of normal ranges. The dark red division is the first that indicates where mean temperatures surpass historic maximum temperatures. Violet zones display areas in which mean temperatures travel twice as far out of the comfort zone as dark red areas.



Temperature Change Severity towards the 2080s
in Central America, Mexico, and the Dominican Republic
B2 Scenario

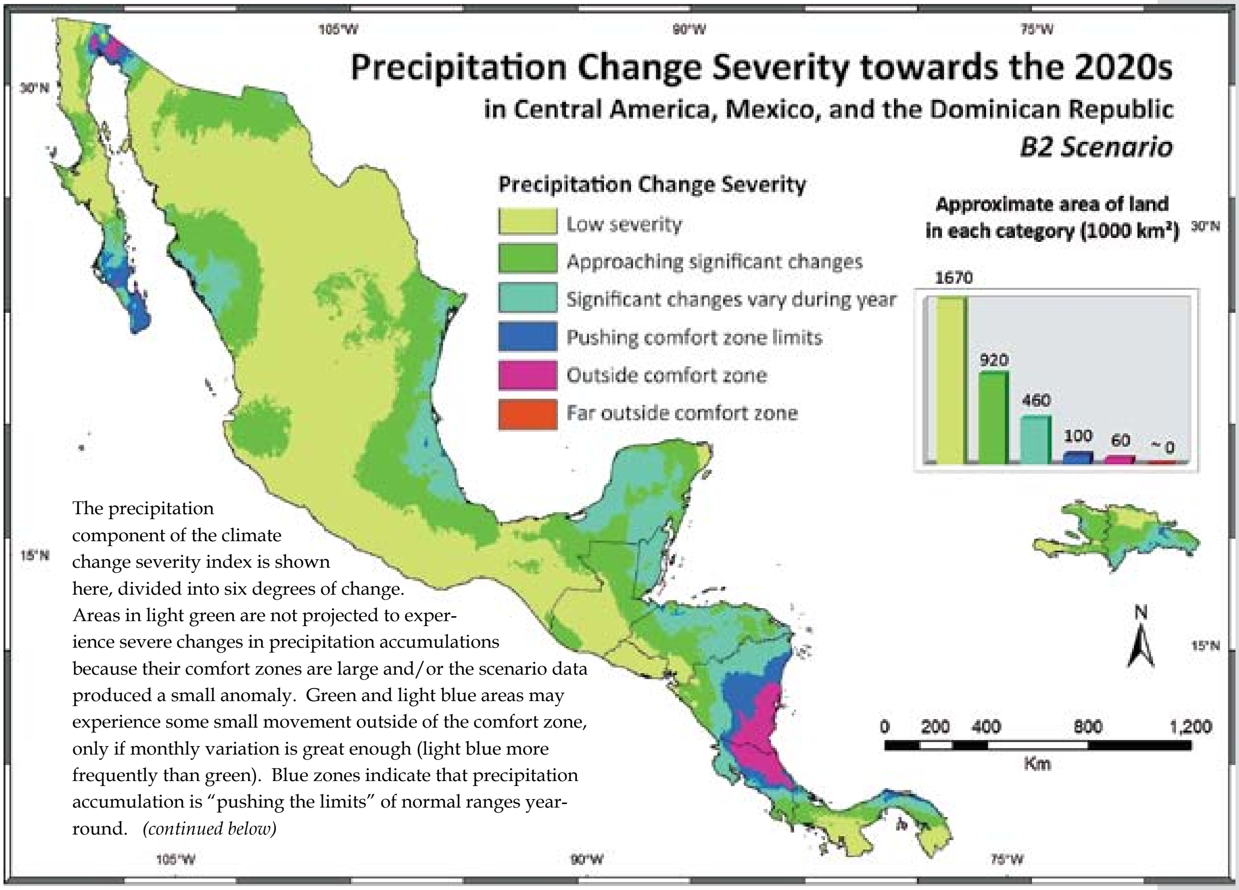
The previous page shows that the only places with projected severe changes in temperature are in the south—nearly all in Panama and small pieces of land in Guatemala and Mexico. There are barely any noticeable differences between the A2 and B2 scenarios in the 2020s, including slightly higher severity in Nicaragua (in orange). During the 2080s, there is a much more noticeable difference between A2 and B2 scenarios. The histograms on each of these maps illustrate the *(continued below)*



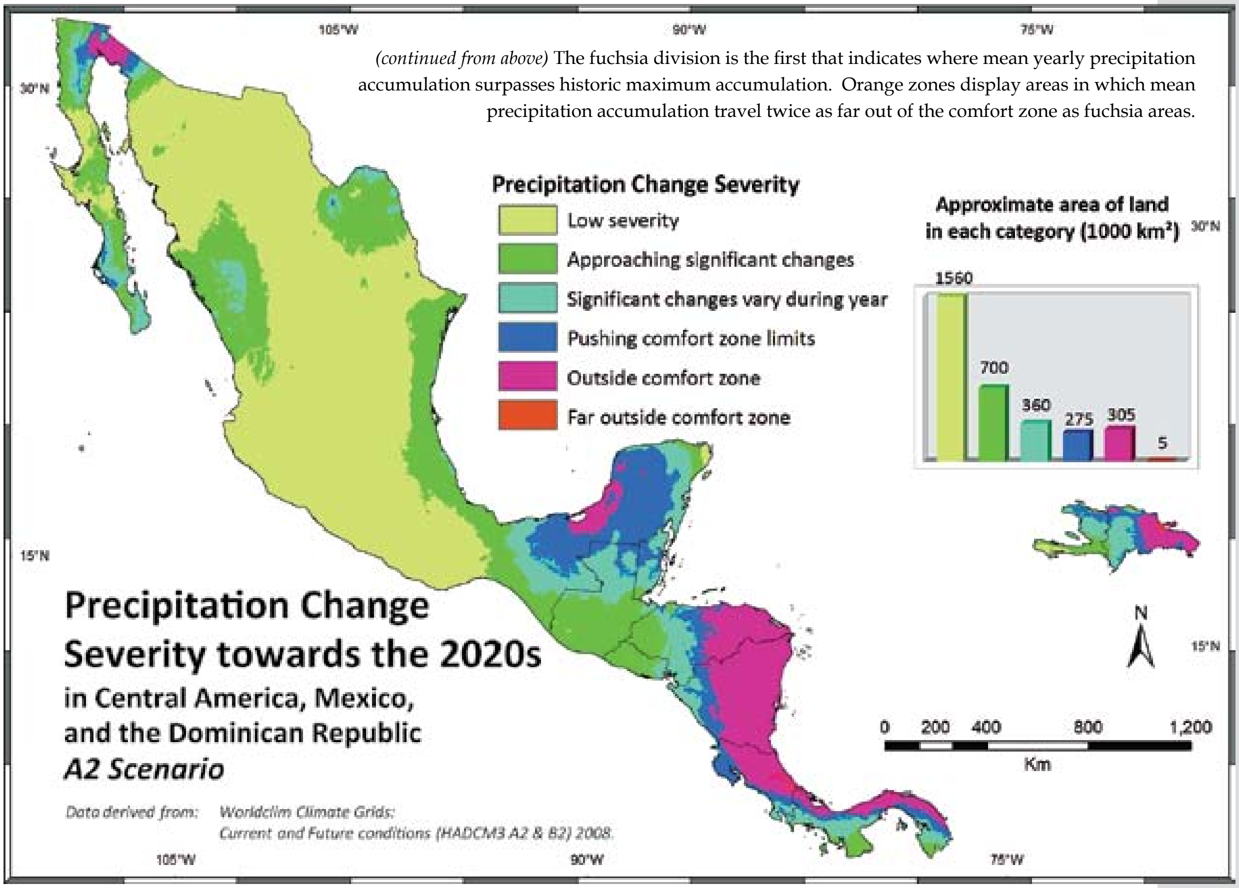
(continued from above) approximate area of land in each category of temperature change severity. There is a substantial increase in severity toward the 2080s, especially noticeable in the last three classes (red, dark red, and purple). Also worth noting is the shift of temperature change severity towards the north over time.

Temperature Change Severity towards the 2080s
in Central America, Mexico, and the Dominican Republic
A2 Scenario

Data derived from: Worldclim Climate Grids: Current and Future conditions (HADCM3 A2 & B2) 2008.

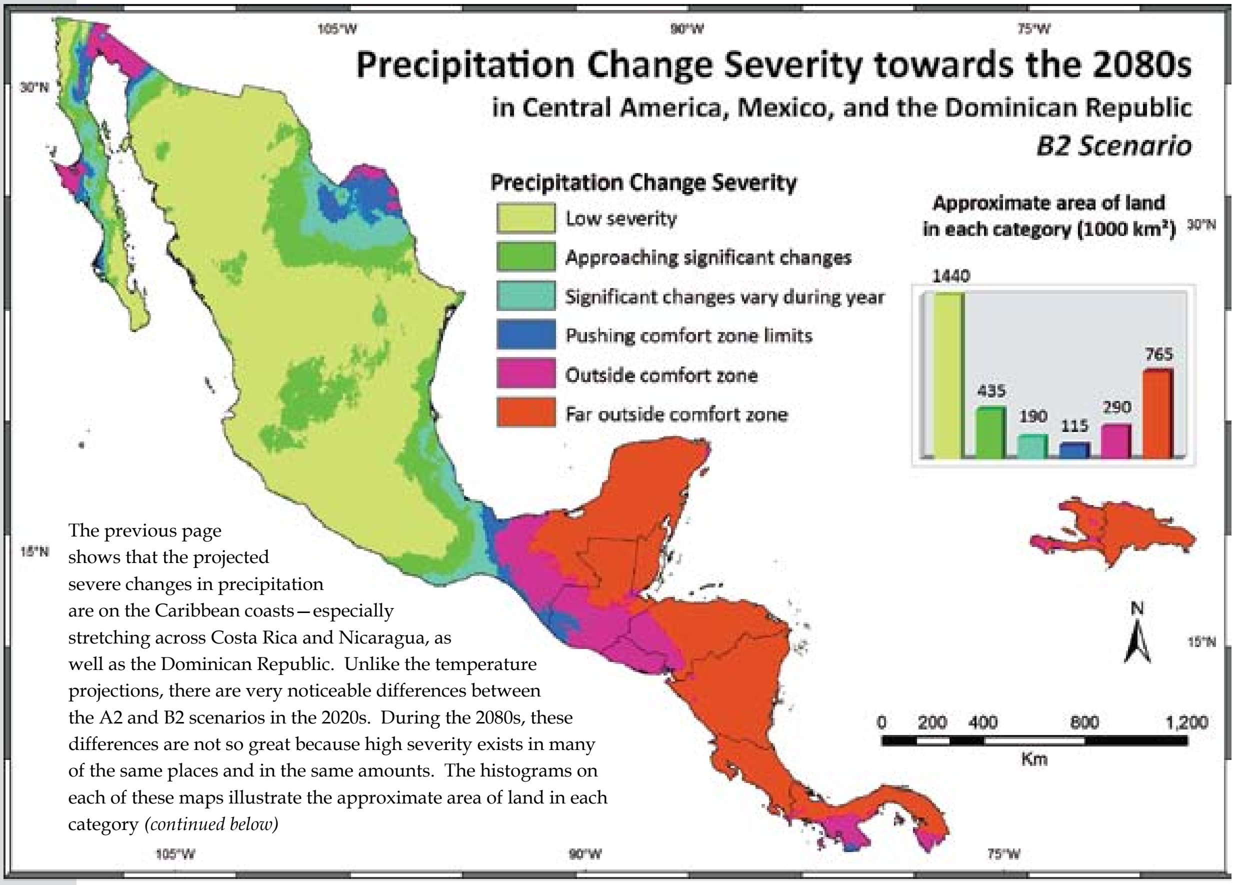


The precipitation component of the climate change severity index is shown here, divided into six degrees of change. Areas in light green are not projected to experience severe changes in precipitation accumulations because their comfort zones are large and/or the scenario data produced a small anomaly. Green and light blue areas may experience some small movement outside of the comfort zone, only if monthly variation is great enough (light blue more frequently than green). Blue zones indicate that precipitation accumulation is "pushing the limits" of normal ranges year-round. *(continued below)*

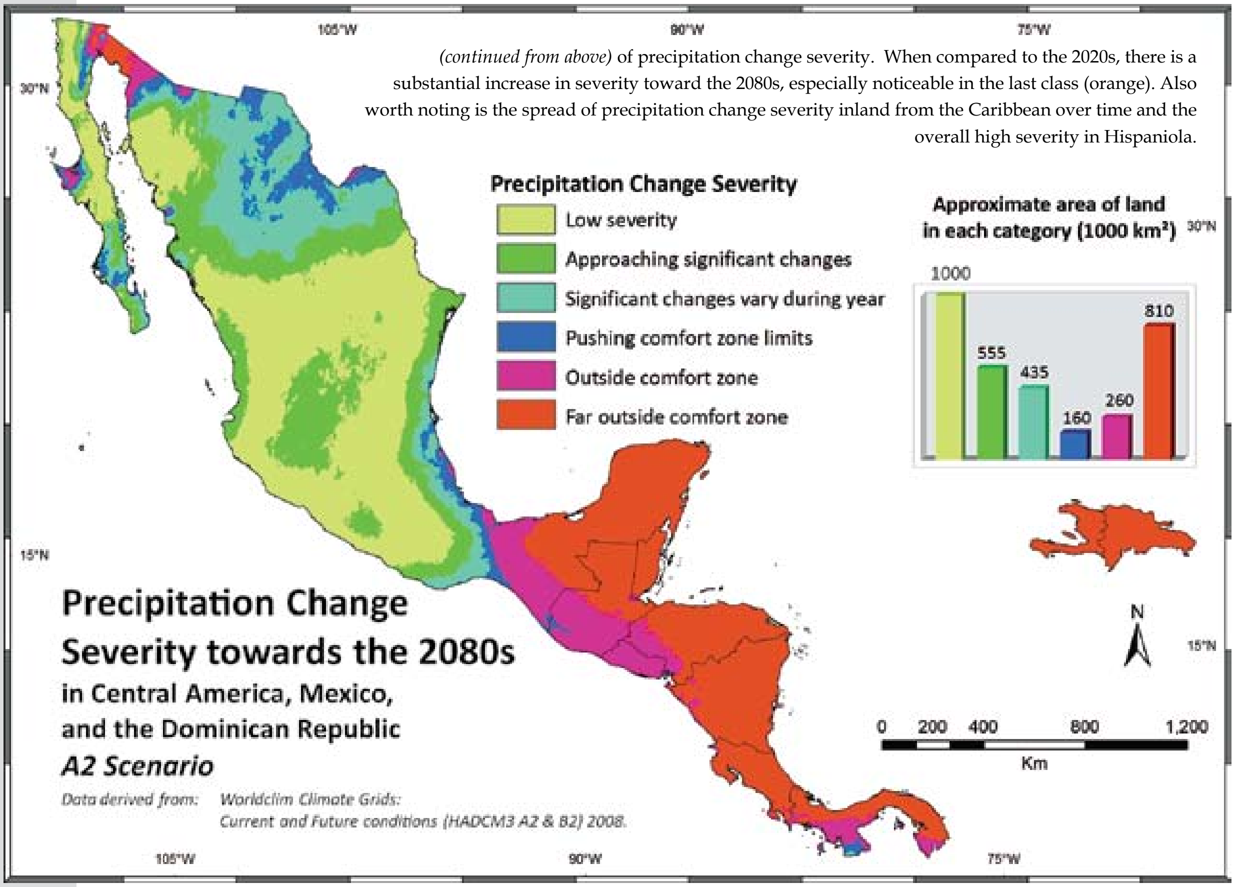


(continued from above) The fuchsia division is the first that indicates where mean yearly precipitation accumulation surpasses historic maximum accumulation. Orange zones display areas in which mean precipitation accumulation travel twice as far out of the comfort zone as fuchsia areas.

Data derived from: Worldclim Climate Grids: Current and Future conditions (HADCM3 A2 & B2) 2008.



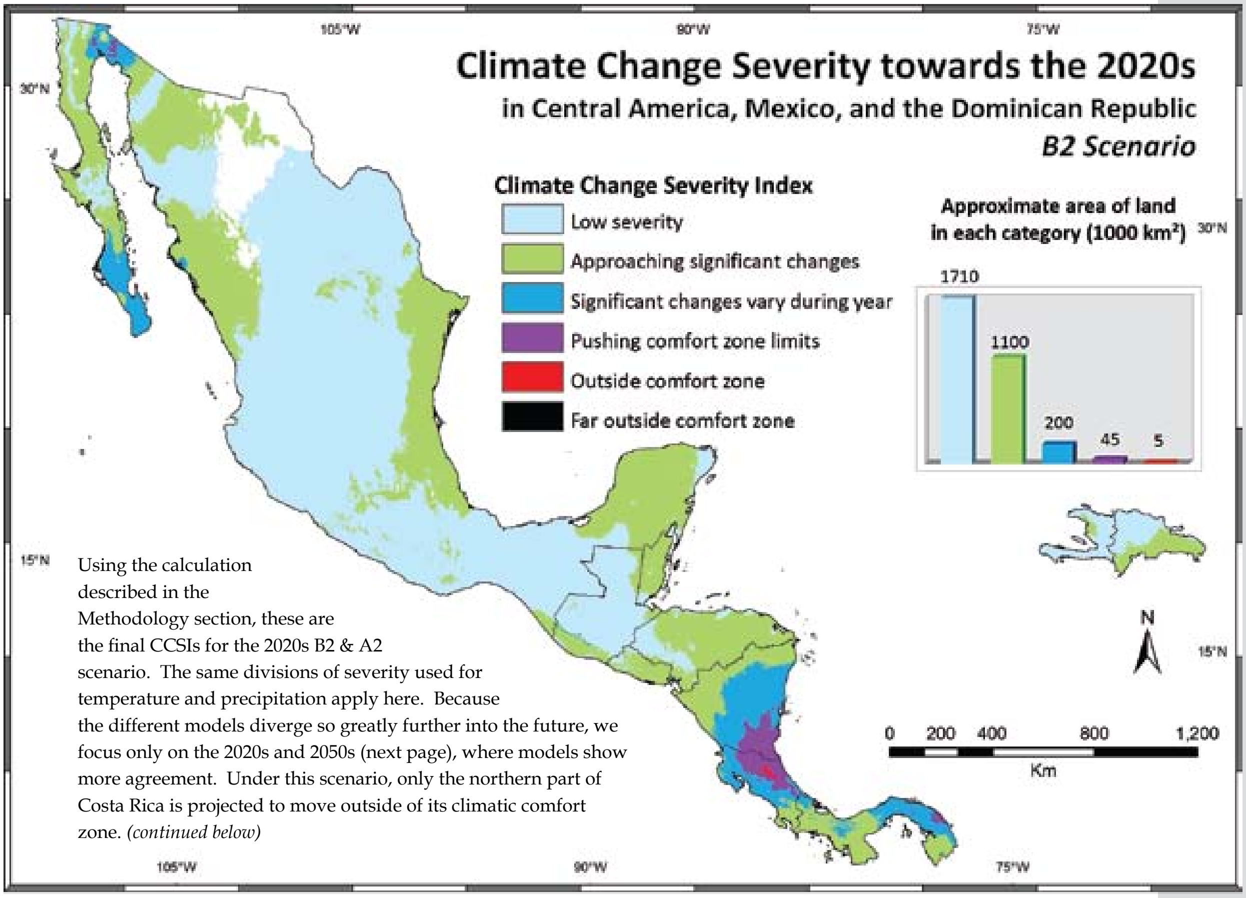
The previous page shows that the projected severe changes in precipitation are on the Caribbean coasts—especially stretching across Costa Rica and Nicaragua, as well as the Dominican Republic. Unlike the temperature projections, there are very noticeable differences between the A2 and B2 scenarios in the 2020s. During the 2080s, these differences are not so great because high severity exists in many of the same places and in the same amounts. The histograms on each of these maps illustrate the approximate area of land in each category *(continued below)*



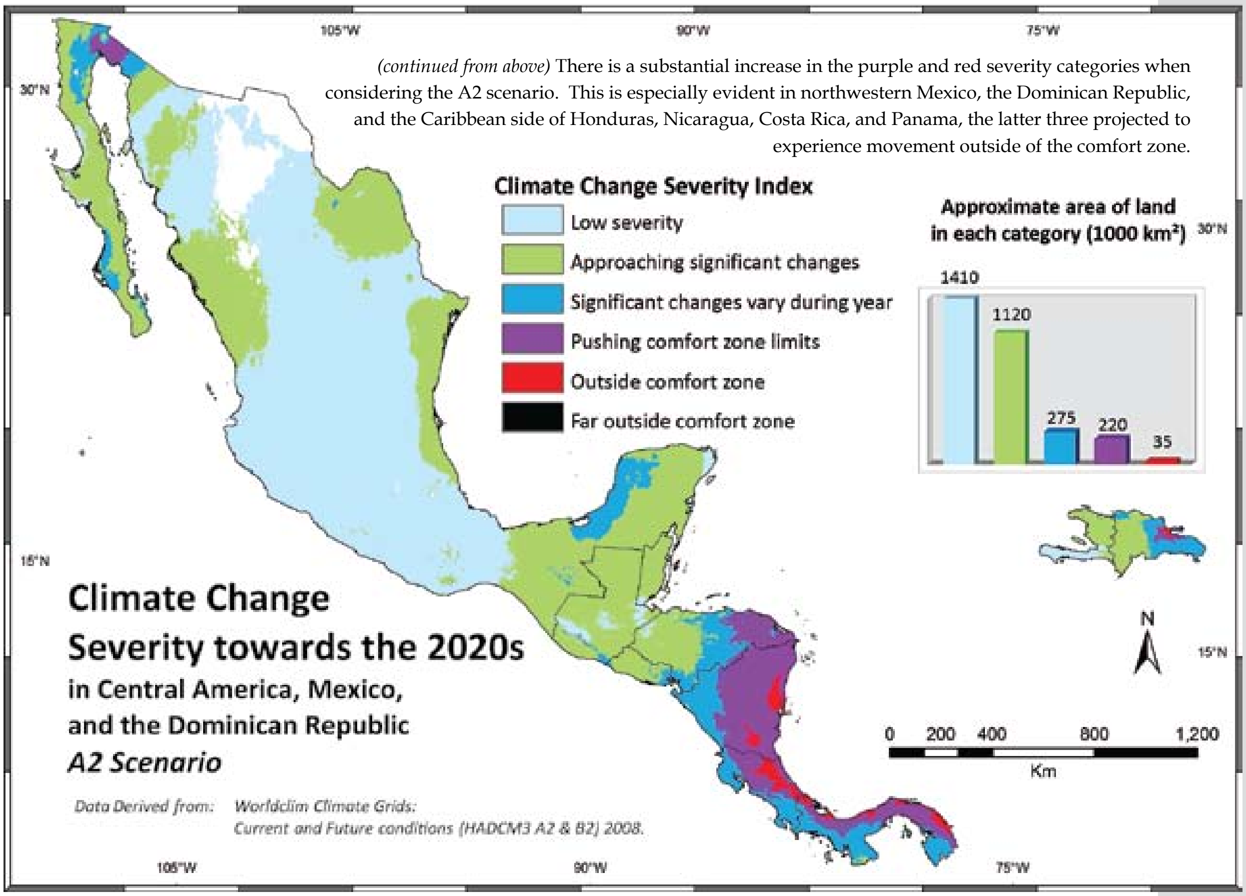
(continued from above) of precipitation change severity. When compared to the 2020s, there is a substantial increase in severity toward the 2080s, especially noticeable in the last class (orange). Also worth noting is the spread of precipitation change severity inland from the Caribbean over time and the overall high severity in Hispaniola.

Precipitation Change Severity towards the 2080s
in Central America, Mexico, and the Dominican Republic
A2 Scenario

Data derived from: Worldclim Climate Grids: Current and Future conditions (HADCM3 A2 & B2) 2008.

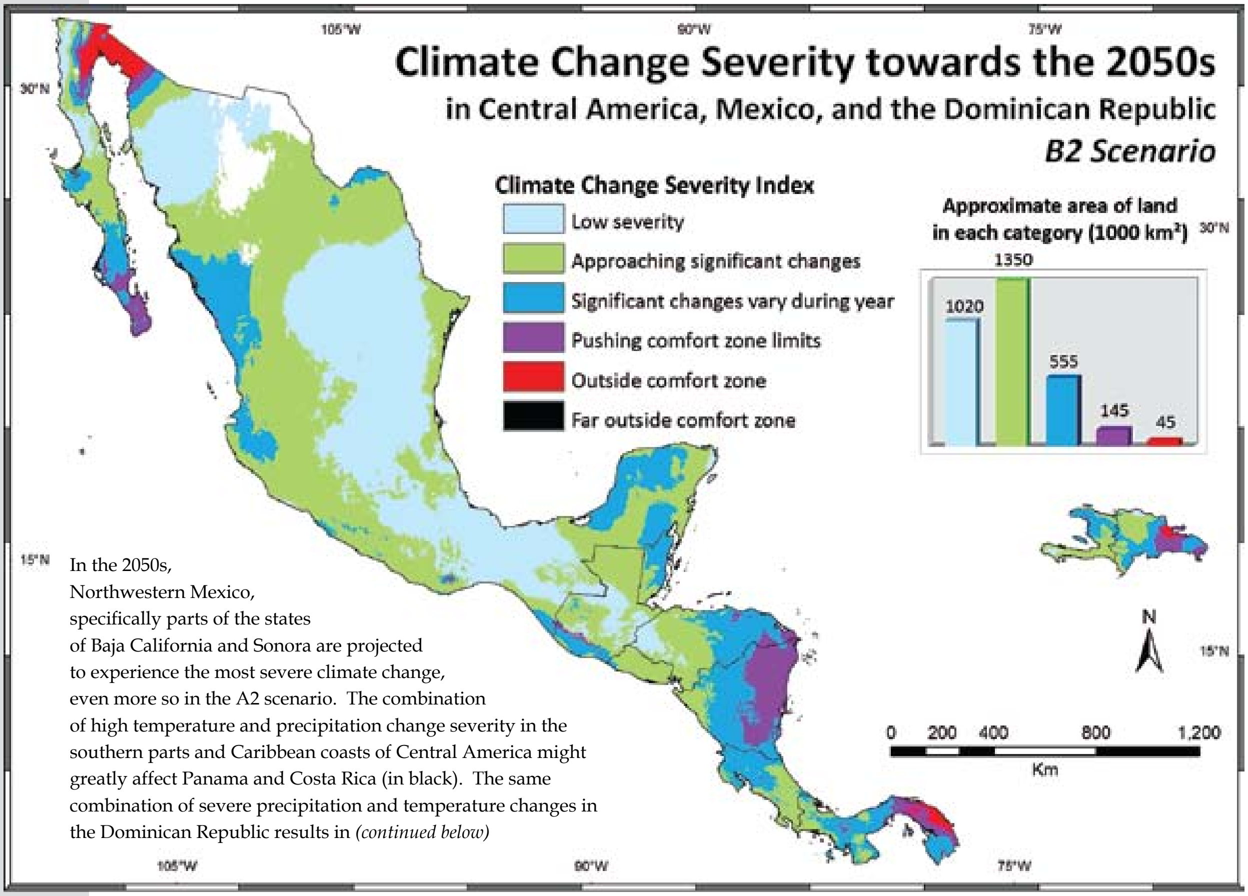


Using the calculation described in the Methodology section, these are the final CCSIs for the 2020s B2 & A2 scenario. The same divisions of severity used for temperature and precipitation apply here. Because the different models diverge so greatly further into the future, we focus only on the 2020s and 2050s (next page), where models show more agreement. Under this scenario, only the northern part of Costa Rica is projected to move outside of its climatic comfort zone. *(continued below)*

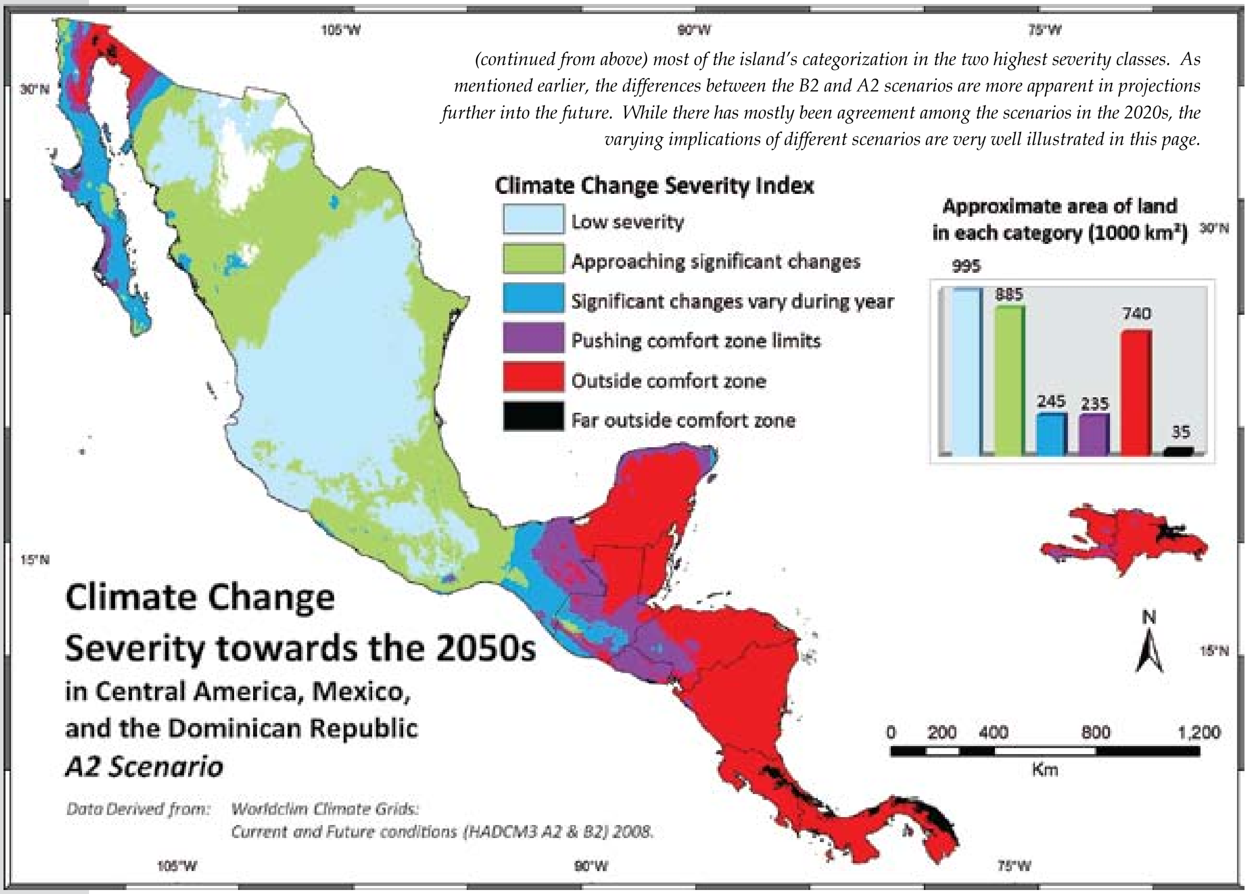


(continued from above) There is a substantial increase in the purple and red severity categories when considering the A2 scenario. This is especially evident in northwestern Mexico, the Dominican Republic, and the Caribbean side of Honduras, Nicaragua, Costa Rica, and Panama, the latter three projected to experience movement outside of the comfort zone.

Data Derived from: Worldclim Climate Grids: Current and Future conditions (HADCM3 A2 & B2) 2008.



In the 2050s, Northwestern Mexico, specifically parts of the states of Baja California and Sonora are projected to experience the most severe climate change, even more so in the A2 scenario. The combination of high temperature and precipitation change severity in the southern parts and Caribbean coasts of Central America might greatly affect Panama and Costa Rica (in black). The same combination of severe precipitation and temperature changes in the Dominican Republic results in *(continued below)*



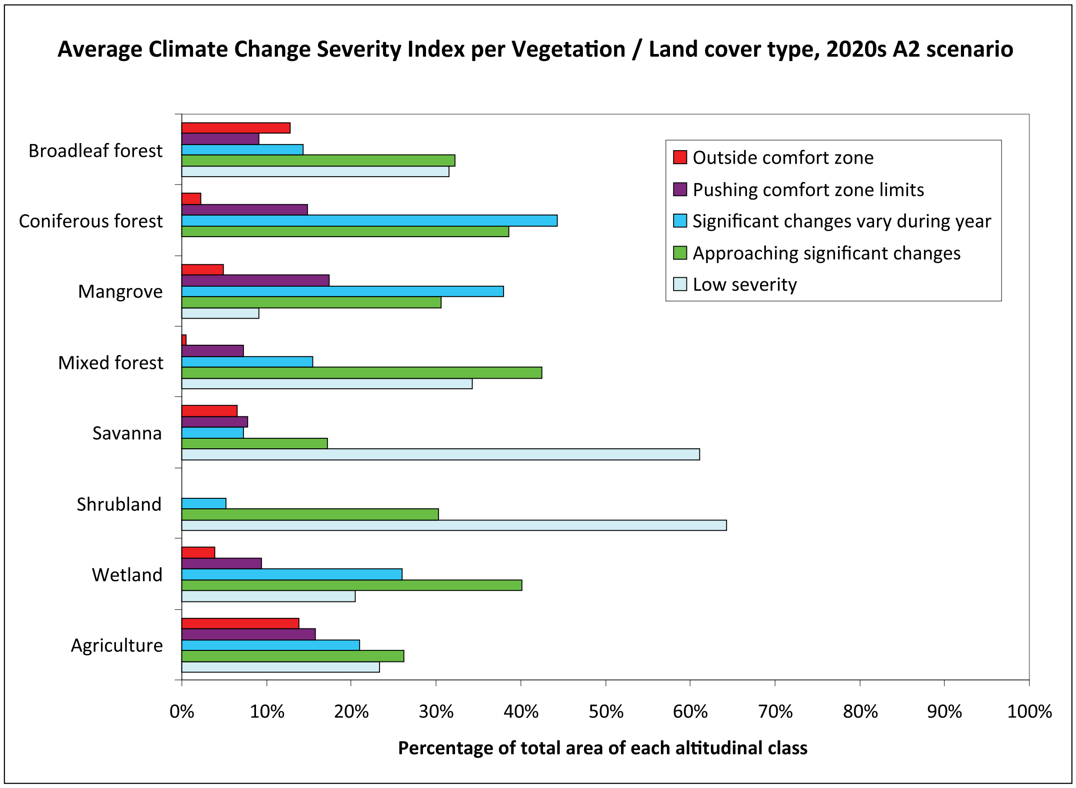
(continued from above) most of the island's categorization in the two highest severity classes. As mentioned earlier, the differences between the B2 and A2 scenarios are more apparent in projections further into the future. While there has mostly been agreement among the scenarios in the 2020s, the varying implications of different scenarios are very well illustrated in this page.

Data Derived from: Worldclim Climate Grids: Current and Future conditions (HADCM3 A2 & B2) 2008.

Impact on Ecosystems

With regard to the CCSI averages for the 2020s for ecosystems, the following trends have been observed. Comparing the CCSI to ecosystems and species is a step towards showing places where rapid adaptation of vegetation and species must occur if these projections ring true. In this sense, "adaptation" most likely means migration, because species will follow the environmental conditions in which they are most comfortable. Many sensitive species could be threatened by habitat loss when more aggressive species move in to its niche. Invasive plants are an especially important topic to consider when monitoring the changes within and around ecosystems.

Unlike the anomaly and severity index maps shown before, this type of climate change severity analysis is not designed to locate actual places that climate change is projected to be the most severe. Rather, it should give an idea of the potential impacts of climate change within different ecosystems as a whole and also at different elevations. Significant consideration should be given to those ecosystems that have very small extents and a very high average CCSI. Such vegetation at the given altitude is at higher risk of being impacted by climate changes. The following graphs inform us of general trends of the potential impact of climate change on ecosystems, in terms of vegetation / land cover and altitude, under the A2 scenario in the 2020s. Other scenarios are discussed further.



With regard to the results presented in Figure 28, it should be noted that in the 2020s under the A2 scenario, there are actually no ecosystems that will experience conditions far outside their comfort zone. However, by the 2050s and 2080s, this degree of climate change severity is reached. Regardless, reviewing the ecosystem map presented earlier and the CCSI maps for the region, the most striking result is that broadleaf forests are projected to experience a significantly high percentage of severe climate change. Savannas and mangroves also have considerable amounts of highly susceptible areas. It is evident from the ecosystem map that shrubland, broadleaf forests, and agriculture are the most extensive land cover types. That nearly a quarter of the broadleaf forests have a high severity index is cause for concern. Some 30% of agricultural areas are also projected to experience highly severe climatic changes.

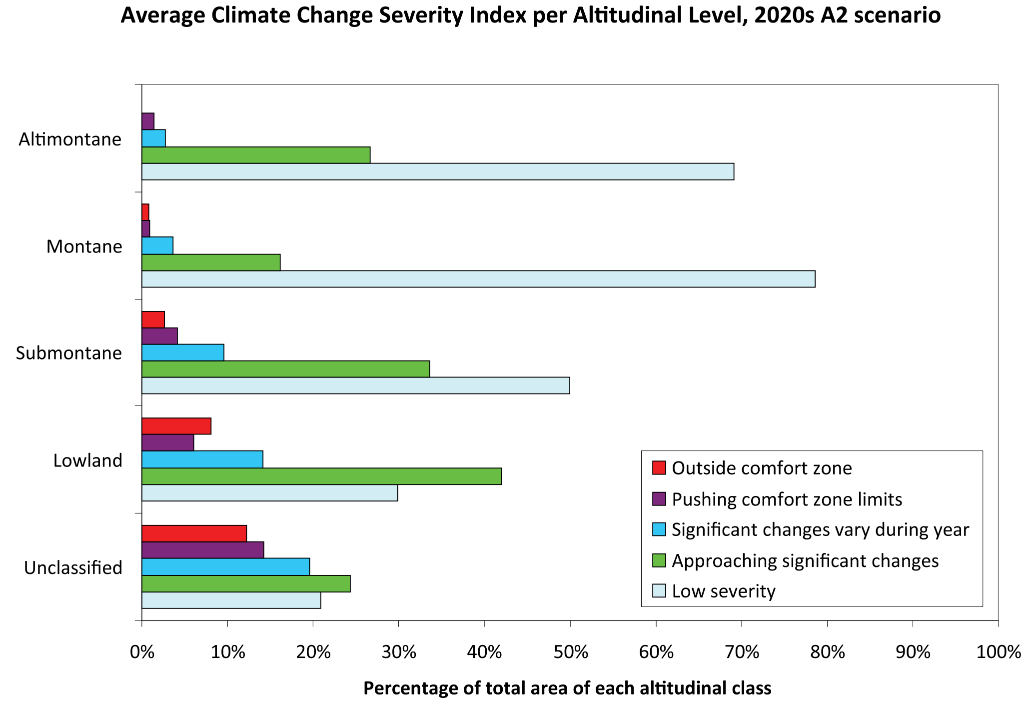


Figure 29 Average CCSI per altitude class, for the 2020s time period, Hadley A2 scenario

In terms of altitude, there seems to be a decreasing trend of severity with increasing elevation. This is most likely because ecosystems at higher altitudes are more adapted to greater ranges in temperature; thus, they could potentially be more resilient to the changes in climate. Conversely, it is important to keep in mind the other factors that could put montane ecosystems at risk, such as invasive species—not only animal but plants as well. These graphs alone do not express these types of threats to ecosystems, but climate change will unequivocally be a driver of species invasion. More detailed histograms for each ecosystem are available in Appendix B.

Obviously the calculations of CCSI per ecosystem and altitudinal class would result in higher severity using the A2 scenario. The following are general differences between the B2 and A2 scenarios, regarding both types of classification. In the B2 scenario, projected climate change is pushing the comfort zone limits or is outside the comfort zone (purple or red) in only submontane, lowlands and unclassified altitudinal classes. Broadleaf forests and agriculture comprise the majority of the most severe climatic changes, while mixed forest and very small amounts of urban areas lie in the "pushing the limits" category. As seen in the previous maps, these classes of higher severity lie in parts of Costa Rica, Panama, Nicaragua, and northwestern Mexico. There is a visible spread of climate change severity in the A2 scenario, which results in high severity in all elevation classes. Although still dominated in lowlands and unclassified, submontane and montane areas have a substantial amount of red and purple zones—evident in Figure 29. As seen in Figure 28, broadleaf forests and agriculture have the highest percentage of climate changes that are projected to move outside of the comfort zone. In the A2 scenario, every class of vegetation or land cover type except shrubland is projected to experience movements outside of the comfort zone as early as 2011 (the 2020s time period). While only a few countries have the higher severity classes in the B2 scenario, every country is projected to experience these change, except for Belize, El Salvador, and Guatemala. According to the CCSI maps displayed earlier, by the 2050s, it is possible that movement outside of the comfort zone will occur somewhere in every country considered in this study.

Integrating the analyses: *Critical habitats*

In addition to the overall trends that can be seen with regard to which areas are likely to be affected by climate change, the results of this study can also be examined more closely from the perspective of the integration of climate severity with specific ecosystems. As mentioned previously in the Methodology section, the CCSI is a measure of how far a location will be placed outside of its current climate comfort zone.

We complement this analysis of ecosystem impact with the identification of critical habitats. This is the combination of species richness and severity of climate changes. While the values are somewhat arbitrary, those chosen in order to identify critical habitats are as follows:

- Highest 10th percentile of species richness, per country
- CCSI of 0.75 or higher

Where these criteria intersect is deemed to be a "critical habitat" (Figure 30). Also displayed on the following two maps are the protected areas. One should be able to determine if these networks of preserved land are adequately placed to prepare for potential impacts of climate change on biodiversity.

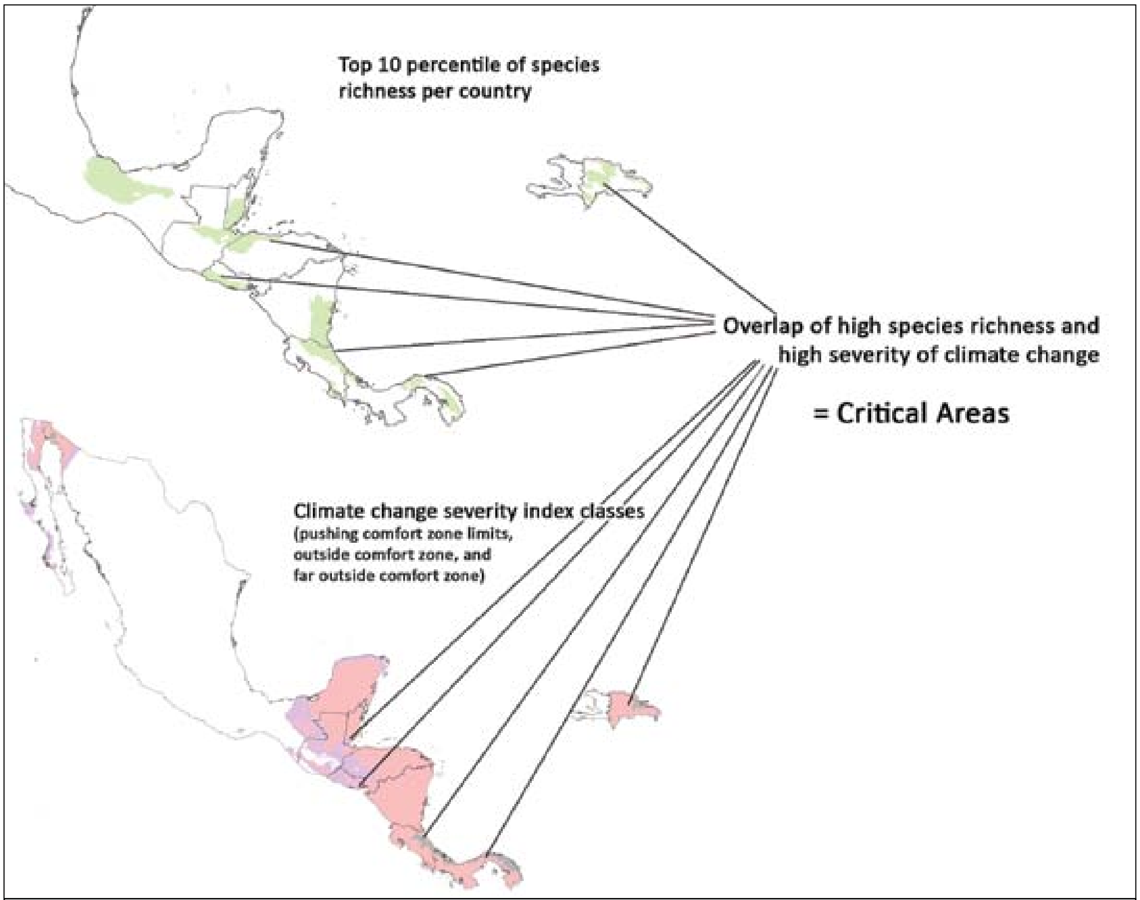
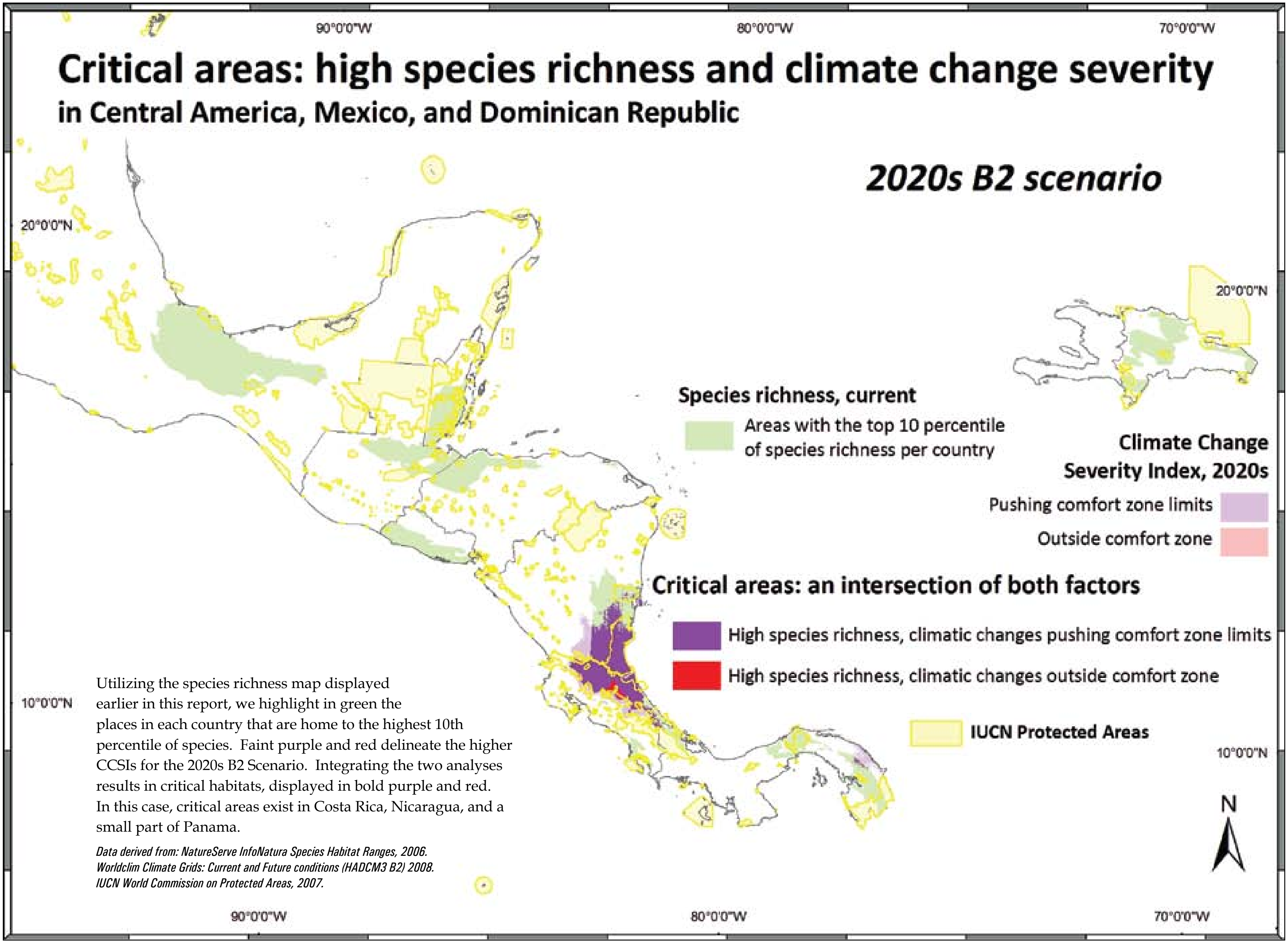
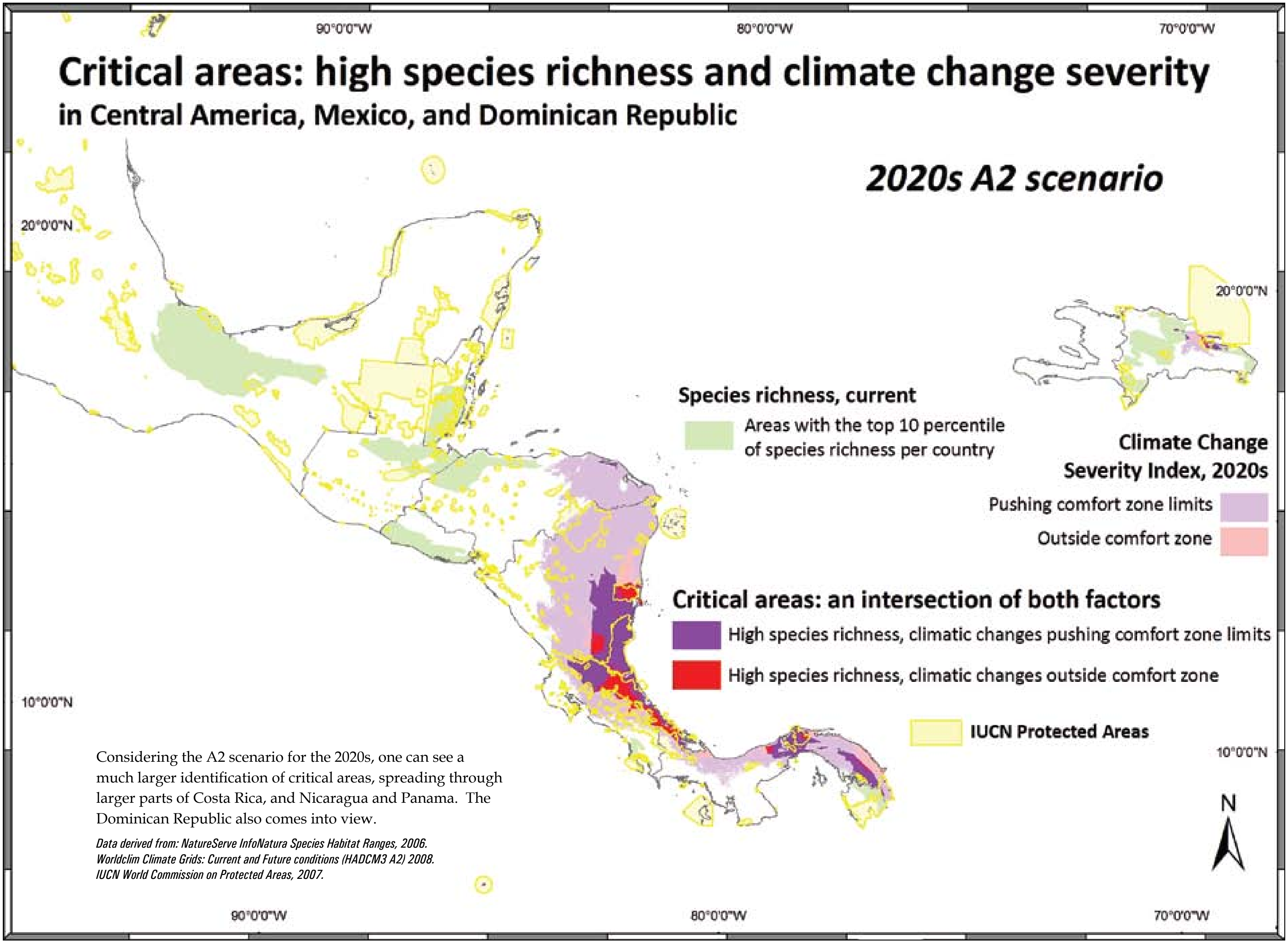


Figure 30 *Conceptual model for identifying critical areas, considering high species richness and highest severity of climate changes, as described in the text above*



Utilizing the species richness map displayed earlier in this report, we highlight in green the places in each country that are home to the highest 10th percentile of species. Faint purple and red delineate the higher CCSIs for the 2020s B2 Scenario. Integrating the two analyses results in critical habitats, displayed in bold purple and red. In this case, critical areas exist in Costa Rica, Nicaragua, and a small part of Panama.

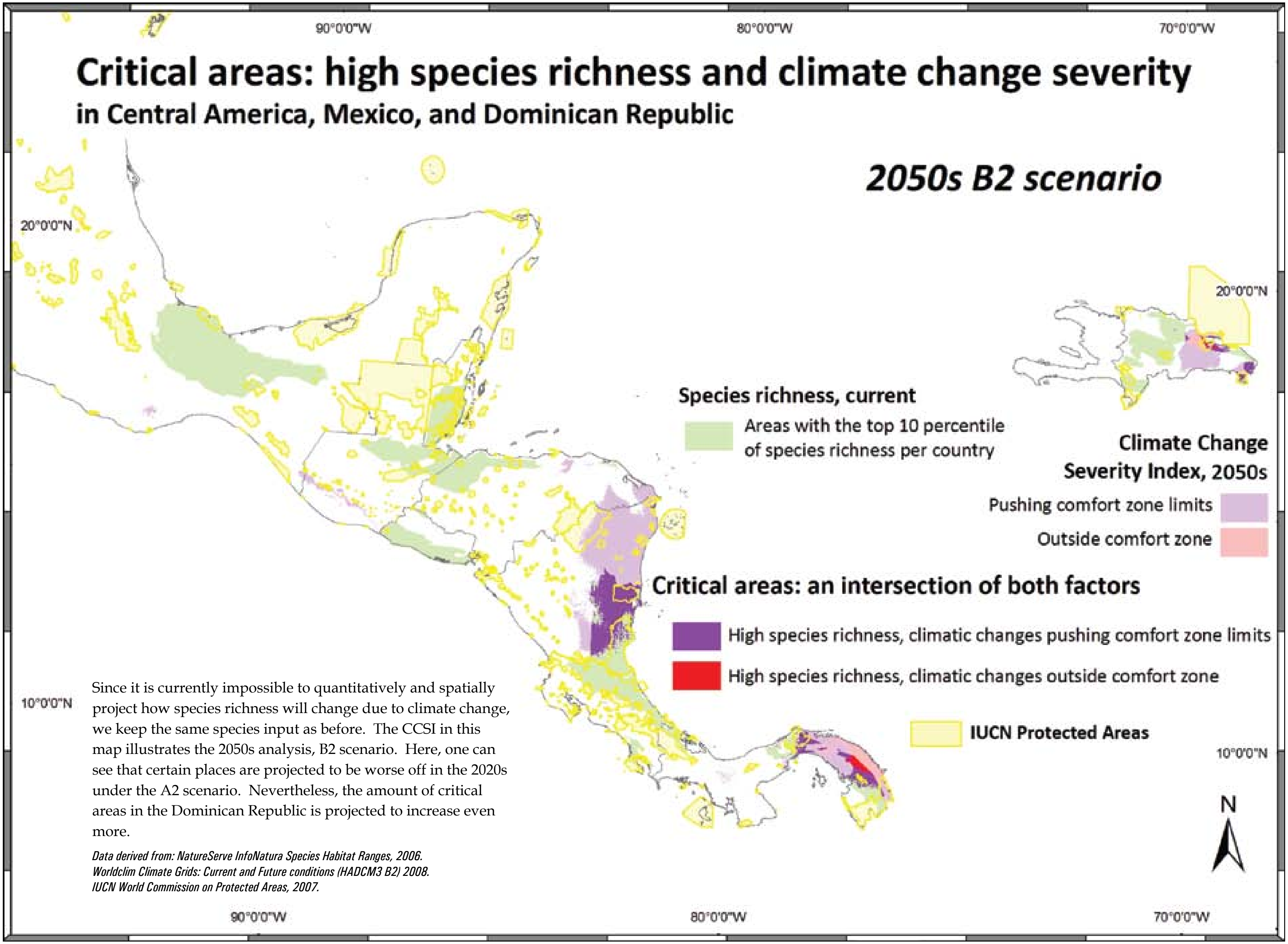
Data derived from: NatureServe InfoNatura Species Habitat Ranges, 2006.
Worldclim Climate Grids: Current and Future conditions (HADCM3 B2) 2008.
IUCN World Commission on Protected Areas, 2007.



Critical areas: high species richness and climate change severity
in Central America, Mexico, and Dominican Republic

Considering the A2 scenario for the 2020s, one can see a much larger identification of critical areas, spreading through larger parts of Costa Rica, and Nicaragua and Panama. The Dominican Republic also comes into view.

Data derived from: NatureServe InfoNatura Species Habitat Ranges, 2006.
Worldclim Climate Grids: Current and Future conditions (HADCM3 A2) 2008.
IUCN World Commission on Protected Areas, 2007.



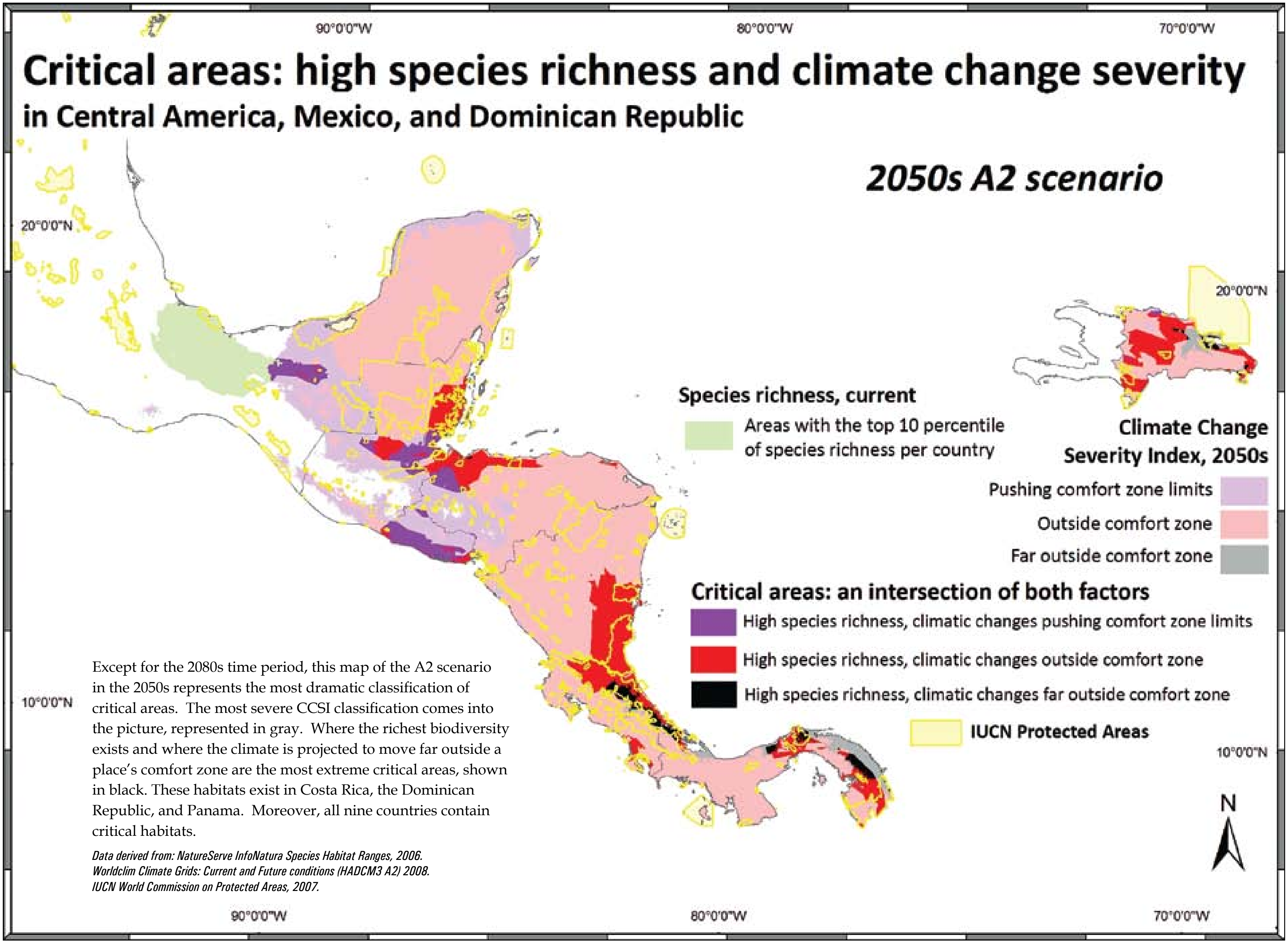
Critical areas: high species richness and climate change severity
in Central America, Mexico, and Dominican Republic

2050s B2 scenario

Since it is currently impossible to quantitatively and spatially project how species richness will change due to climate change, we keep the same species input as before. The CCSI in this map illustrates the 2050s analysis, B2 scenario. Here, one can see that certain places are projected to be worse off in the 2020s under the A2 scenario. Nevertheless, the amount of critical areas in the Dominican Republic is projected to increase even more.

Data derived from: NatureServe InfoNatura Species Habitat Ranges, 2006.
Worldclim Climate Grids: Current and Future conditions (HADCM3 B2) 2008.
IUCN World Commission on Protected Areas, 2007.

Critical areas: high species richness and climate change severity
in Central America, Mexico, and Dominican Republic



Except for the 2080s time period, this map of the A2 scenario in the 2050s represents the most dramatic classification of critical areas. The most severe CCSI classification comes into the picture, represented in gray. Where the richest biodiversity exists and where the climate is projected to move far outside a place's comfort zone are the most extreme critical areas, shown in black. These habitats exist in Costa Rica, the Dominican Republic, and Panama. Moreover, all nine countries contain critical habitats.

Data derived from: NatureServe InfoNatura Species Habitat Ranges, 2006.
Worldclim Climate Grids: Current and Future conditions (HADCM3 A2) 2008.
IUCN World Commission on Protected Areas, 2007.

CONCLUSIONS & RECOMMENDATIONS

From the near-term (2020s) onward, if worst case scenario conditions prevail, the vast majority of the ecosystems of Central America and the Dominican Republic should be affected somehow, likely with varying effects on their constituent species. Mexico, on the other hand, would overall be much less affected. The overall analysis has therefore identified critical areas that may require specific interventions to facilitate the adaptation of species and ecosystems to climate change. It is also worth pointing out that in addition to climate change, ecosystems and species will likely continue to be threatened by deforestation.

In addition to having assessed the potential impacts of climate change on biodiversity, we have also presented a novel framework with which climate change impacts can be analyzed, irrespective of data source, resolution or scenario. This study has focused on presenting which species-rich places and ecosystems would be impacted by climate change according to the worst case (A2) scenario and a better case scenario (B2), giving life to the implications of different possible future. Still, further work should also assess the impacts of climate change under other scenarios, which are so numerous.

While species richness analyses such as this have already been carried out and are available in online maps, the results presented in this report are of much higher spatial resolution. One can also see some overlap with high levels of endemic amphibians and severe climate change. Because the results are in GIS (geographical information systems) format, there is the potential to develop interactive applications in which users can click on any location in the region to discover not only the richness, but also the names of all birds, mammals, and amphibians inhabit that place. Other attributes such as habitat range and status (e.g., endangered, threatened) could be included as well. Further investment in such an application would be very beneficial in many areas such as environmental impact assessments and delineation of biological corridors.

Earlier we remarked that studies of genetic biodiversity at the regional level are likely out of the question; however, there are some potentially useful representations of this measurement, which can possibly be displayed in the same format as the species richness presented in this study. Upon identifying the species in an area, one can do a crude calculation of genetic variety of the area, based on matrix of the genetic "distance" of each species to the other species in the same area. It should be possible to construct this by using a tree of life (Maddison 2007). While much more intensive, within species measurements of genetic diversity could describe the potential adaptive ability of species. The scope of analysis would be much finer, as it would consider a single type of species. What we should expect though is that species will not adapt as quickly in terms of their genetic code (especially animals with long life spans and low reproductive rates) as fast as they will shift habitat ranges—as they are already doing.

Although the temperature and precipitation anomaly concept is not new to the schema of analyses, we still include these in our report because they present some of the many ways climate change scenarios can be analyzed. Since the data used is so new and of high resolution, heavy analysis was required to determine and illustrate the precipitation and temperature anomaly graphs of six scenarios for all of the country capitals (Appendix A). These give an idea of the agreement or variety among different models and scenarios.

Temperature change projections are much more in accordance in the 2020s than in the 2050s and 2080s. This is useful information because we should be able to more confidently expect a regional rise of 1˚C as early as 2011 (when compared to the 1961-1990 baseline). As we have seen in the country maps, some locations may experience nearly 2˚C, and others less.

General tendencies in precipitation changes are much more difficult to project than temperature, even in the not-too-distant future. Not only does the quantity of precipitation change differ from scenario to scenario, but also does the actual location of these precipitation changes. On the other hand, there is a general trend among nearly all the models that there could be drier wet seasons. This has significant implications on agriculture and water availability and quality in our region. Moreover, this trend in the drying of the rainy season could have significant impact on forest fires. The scientific consensus is that forest fires in Central America have not played a large role in shaping the region's landscape or in driving vegetation dynamics (Middleton et al. 1997). This may be changing. We can learn from previous events such as the 1997-1998 El Niño, in which there was significantly less rain in the wet season in Panama. Some of the many impacts included a lack of water in the Panama Canal watershed—both for canal operations, drinking water, and fishing—as well as a marked increase in area burned due to forest fires (Donoso et al. 2000; López 2004).

Anomaly data is invaluable to many biologists who are interested in absolute temperature ranges for a species of interest; however, it does not express an overall idea of how much climate change will affect different parts of the region as a whole. Moreover, it does not take into consideration any measure of climate variability. The climate change severity index attempts to address these issues. In terms of temperature, the severity index states quite the opposite than does anomaly data. Nearly all of the global climate models demonstrate mild increases in temperature at lower latitudes, compared to extreme changes nearing the poles. This is no doubt an important trend for glaciology and studies of the global circulation of temperature and salinity, but it understates the impact that such a small increase could potentially have on tropical ecosystems and species. The tropics experience much smaller changes in annual temperature than northern latitudes (both in terms of day-night ranges and seasonal variations); therefore, the species and ecosystems have developed under temperature low variability. Because of these facts, what could be considered a "mild" change could in fact be devastating (Deutsch 2008).

On the other hand, most countries in Mesoamerica and the Caribbean receive very different amounts of rainfall during the year. Most places have a distinct wet and dry season, which means that the comfort zone for the wet tropics is very large. Therefore, the climate change severity index often is very low on the side of precipitation.

As this study has focused solely on the potential impacts of climate change on terrestrial biodiversity, useful follow-up for this research would include expanding the study to assess the impacts of climate change on aquatic and marine biodiversity. At the publication of this study, most of the requisite inputs for such a modeling effort do not exist. These would include:

- Aquatic and marine species distributions
- Marine pH (multi-depth)
- Marine salinity (multi-depth)
- Marine temperature (multi-depth)

Here we present only temperature and precipitation, but other environmental variables are important as well. Among other models, the SERVIR regional climate scenario includes:

- Soil moisture (multi-depth)
- Moisture content
- Surface temperature
- Sea level pressure
- Wind direction and velocity

Just as there are coupled models in climatology, we should strive to couple high resolution climate scenarios with future land use scenarios. The latter is undoubtedly the major culprit of species endangerment and is the chief threat to biodiversity. Given the current rates of deforestation in Mesoamerica and the Caribbean, it is crucial to include this factor in assessing the potential human impacts on biodiversity. The Millennium Ecosystem Assessment, for example has already established a framework for developing scenarios similar to the SRES for land cover change. Narrative scenarios of future development in Latin America and the Caribbean have been developed by a regional expert group coordinated by the United Nations Environmental Programme's GEO-LAC group. Explicit land cover change scenarios based off these have already been developed for Belize, southern Mexico, and most of Guatemala and Honduras under the UNEP- and USAID-supported ICRAN-MAR project of 2004-07. Applying this project to the CCSI and critical habitats assessment would enhance current impact assessments on biodiversity.

Uncertainty is an omnipresent concept in climate change modeling; however, degrees of uncertainty are not the same for all time frames. These analyses of climate change severity and identification of critical areas show a high level of agreement among various models in the 2020s. We should consider this as strong a signal for what may come in the not-too-distant future, and with the further integration of environmental and social studies, we should be more equipped to adapt to and mitigate the potential impacts of climate change on biodiversity.

ACKNOWLEDGEMENTS

This study was only made possible through the contributions of a variety of professionals, institutions and initiatives. It was conducted as one of the components of the "Mainstreaming Climate Indices & Weather Derivatives into Decision-Making for Adaptation to Climate Change in Central America, Mexico and the Dominican Republic" project. The project is implemented by the Water Center for the Humid Tropics of Latin America and the Caribbean (CATHALAC) through the sponsorship of the Global Development Alliance (GDA) program of the United States Agency for International Development (USAID), and with support from the U.S. National Aeronautics and Space Administration (NASA), the University of Alabama-Huntsville (UAH), Cable and Wireless-Panama, and the Environmental Systems Research Institute (ESRI). In addition to the staff at CATHALAC who worked on this study, invaluable oversight was provided by the USAID in the persons of Orlando Altamirano, Carey Yeager, Carrie Stokes and John Furlow, as well as from NASA in the persons of Daniel Irwin, Woody Turner, and Tom Sever.

This study benefited substantially from the input of the representatives of the nine countries participating in the project. We would like to acknowledge all of the participants of the two GDA-sponsored regional consultations that were held, namely the "Regional Experts Meeting on the Possible Impacts of Global Climate Change on Regional Biodiversity in Mesoamerica and the Dominican Republic" workshop held March 21-22, 2007 in Panama City, and the follow-up "Modeling Biodiversity Vulnerability to Climate Change" workshop held April 21-22, 2008 in Panama City.

National experts consulted at the aforementioned expert meetings included Carlos Fuller, Saul Cruz and Marcelo Windsor from Belize, Carmen Roldán Chacón, Magda Campos and Luis Alvarado Gamboa from Costa Rica, Magali Núñez, German Dominici and Edward Matos from the Dominican Republic, Ana Cecilia Carranza and Enrique Barraza from El Salvador, Claudio Castañón Contreras from Guatemala, Mirza Castro, Claudia Patricia Cortez, Manuel José Rey Figueroa and Héctor Orlando Portillo Reyes from Honduras, Miguel Angel Altamirano, Eduardo Peters Recagno, Alejandro Frías, and Victor Magana from Mexico, Bernardo Torres and Judith Núñez from Nicaragua, and Rene Lopez, Dario Luque and Eliecer Osorio from Panama.

The initial framework for this study was developed by Laura Tremblay-Boyer and Eric Anderson who conducted their research at CATHALAC in the context of the McGill University Panama Field Studies Semester program, jointly with the Smithsonian Tropical Research Institute (STRI). Their study culminated in the development of the methodology called EVCC (Ecosystem Vulnerability to Climate Change).

This study would not have been possible without the wealth of publicly accessible climate and other spatial datasets from a variety of sources. The data utilized included:

- Species habitat range data from NatureServe's InfoNatura database
- Land cover data for Mexico was extracted from the GeoCover LC product developed by the Earth Satellite Corporation (Earthsat)
- Land cover data of the Dominican Republic was obtained from the Caribbean Vegetation Mapping Project funded by the USAID Caribbean Regional Program
- Ecosystem data for Central America from the World Bank and Government of the Netherlands-supported Central America Ecosystem Mapping Project, which was further refined by the Central American Commission for the Environment & Development
- Downscaled climate scenario data from SERVIR project, developed by NASA and Oak Ridge National Laboratory

- Downscaled climate scenario data from the PRECIS Caribbean Climate Change project jointly of the Caribbean Community Climate Change Centre and the Hadley Centre for Climate Prediction & Research
- Downscaled climate scenario data from the WorldClim Consortium
- GCM climate scenario data from the U.S. National Center for Atmospheric Research's GIS Climate Change Scenarios project

Thanks are also due to William Gough from the University of Toronto, and Neil Comer and Adam Fenech from Environment Canada, who led the workshop, "Climate Models: Scenarios of Future Climate Change for Impacts and Adaptation Studies," from March 3-4, 2008 in Panama City, Panama as part of the "Climate Change and Biodiversity in the Americas" Symposium sponsored by Environment Canada and the Smithsonian Institution.

SELECTED BIBLIOGRAPHY

Barry, P.L. 2003. Mesoamerica Burning. National Aeronautics and Space Administration. Washington, DC. http://science.nasa.gov/headlines/y2003/16may_biocorridors.htm (accessed 01/2008)

Canadian Climate Change Scenarios Network [web application]. 2008. Gatineau, Canada: Environment Canada. http://www.cccsn.ca (accessed 03/2008)

Conservation International. 2004. Hotspots Revisited. http://web.biodiversityhotspots.org/xp/Hotspots/hotspotsScience/hotspots_revisited.xml (accessed 04/2008)

Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak, D.C. and P.R. Martin. 2008. Impacts of climate warming on terrestrial ectotherms across latitude. Proceedings of the National Academy of Sciences 105: 6668-6672.

Donoso, M.C., Vargas, C., Leaman, K. Castillero, M., Martinez, D. and M. Nakayama. 2001. Panama Canal Case Study: Impacts and Responses to the 1997-1998 El Niño Event. In: Once Burned, Twice Shy: Lessons Learned from the 1997-98 El Niño. M.H. Glantz (Ed.) UN University Press, Tokyo. 294 pp.

Hernandez, J., Srikishen, J., Erickson, D., Oglesby, R. and D. Irwin. 2006. A Regional Climate Study of Central America using the MM5 Modeling System: Results and Comparison to Observations. International Journal of Climatology 26: 2161-2179.

Hijmans RJ, et al. 2005. Very High Resolution Interpolated Climate Surfaces for Global Land Areas. International Journal of Climatology 25: 1965-1978.

InfoNatura: Animals and Ecosystems of Latin America [web application]. 2007. Version 5.0. Arlington, Virginia (USA): NatureServe. http://www.natureserve.org/infonatura (accessed 01/2008)

López, M.A. 2004. Central America and Mexico Regional Brief on International Cooperation in Wildland Fire Management. Pan-American Wildland Fire Conference. 21-24 October 2004. San José, Costa Rica.

Pounds, A.J., Bustamante, M.R., Coloma, L.A., Consuegra, J.A., Fogden, M.P.L., Foster, P.N., La Marca, E., Masters, K.L., Merino-Viteri, A., Puschendorf, R., Ron, S.R., Sanchez-Azofeifa, G.A., Still, C.J., and B.E. Young. 2006. Widespread amphibian extinctions from epidemic disease driven by global warming. Nature 439: 161-167.

Maddison, D.R., Schulz K-S., and W.P. Maddison. 2007. The Tree of Life Web Project. Zootaxa 1668: 19-40.

IPCC Special Report Emissions Scenarios, Summary for Policymakers. 2000. Intergovernmental Panel on Climate Change. 27 pp.

Tremblay-Boyer, L. and E.R. Anderson. 2007. Preliminary Analysis of Ecosystem Vulnerability to Climate Change in Panama. Senior Research Project: McGill University, Montreal, Canada; and CATHALAC, Panama City, Panama. http://evcc-panama.mcgill.ca (accessed 11/2007)

Vreugdenhil, D., Meerman, J., Meyrat, A., Gómez, L.D., and D.J. Graham. 2002. Map of the Ecosystems of Central America: Final Report. World Bank, Washington, DC. 56 pp.

World Bank & CCAD. 2001. Ecosystems of Central America (ArcView regional map files at 1:250,000). World Bank, Central American Commission on Environment and Development (CCAD), World Institute for Conservation and Environment (WICE), and the Centro Agronómico Tropical de Investigación y Enseñanza (CATIE), Washington, DC. http://www.worldbank.org/ca-env (accessed 05/2008)

APPENDIX A: COUNTRY PROFILES

Where the main body of this report focuses on presenting the results of the modeling at a regional level, these appendices provide a more detailed look per country with regard to the following:

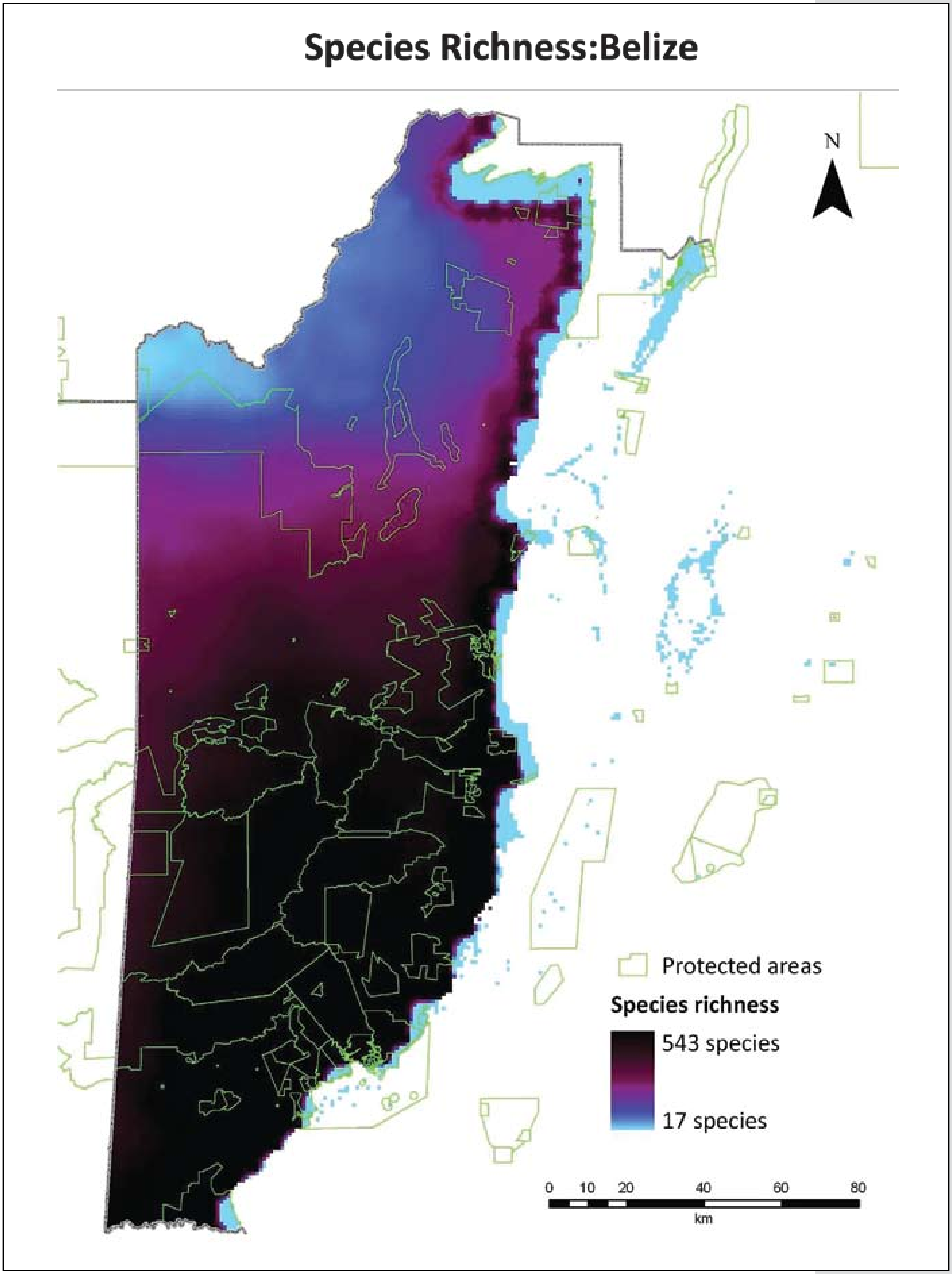
- Species richness
- Future temperature anomalies (baseline and Hadley A2 scenarios: 2020s and 2080s)
- Future precipitation anomalies (baseline and Hadley A2 scenario: 2020s)
- Variation between six scenarios (per capital city)
- Severity of temperature and precipitation changes as well as overall climate change severity index (Hadley A2 scenario: 2020s)

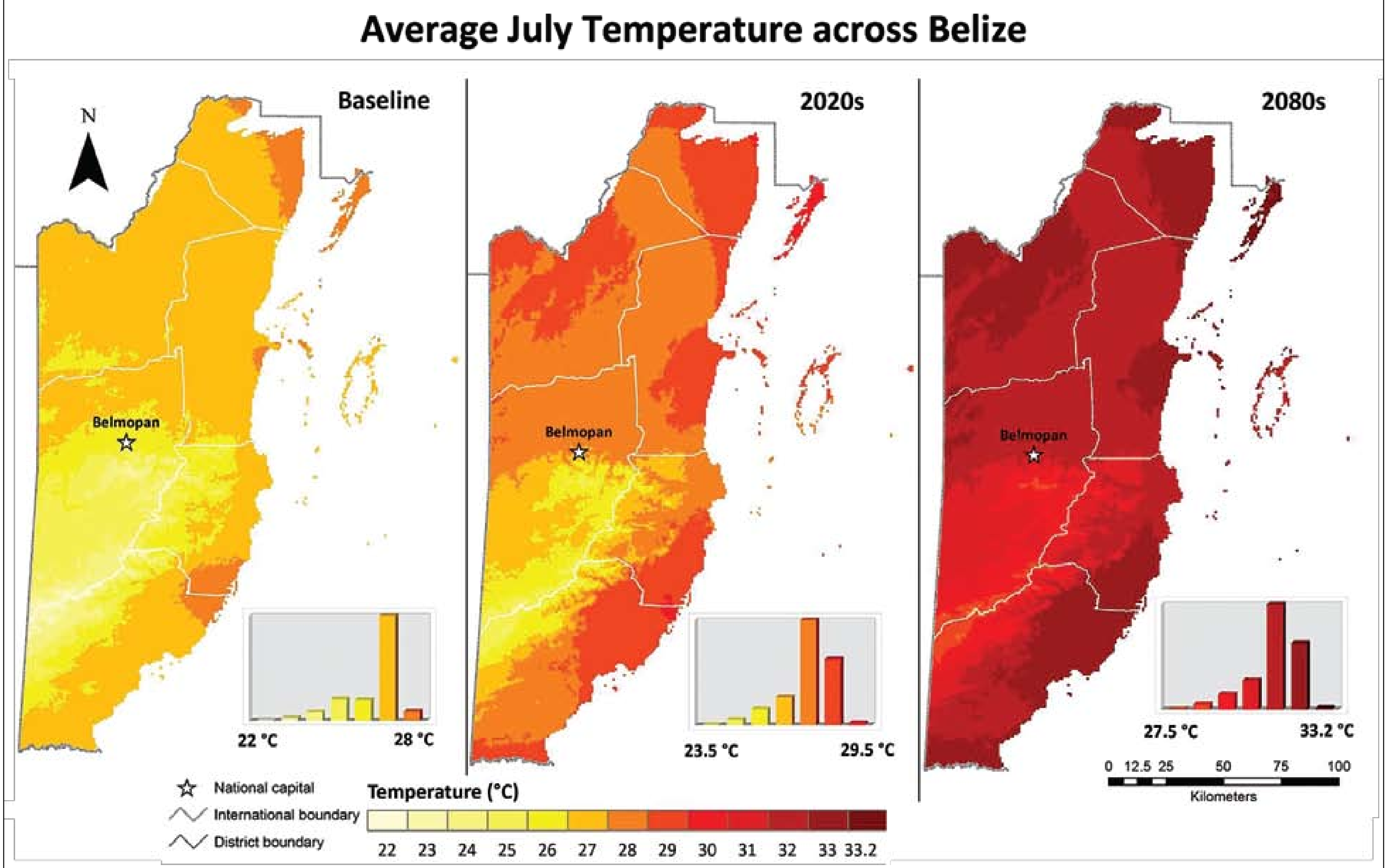
The simple five pages of graphics for each country are meant to be illustrative, allowing someone familiar with a particular country to easily see which areas might be impacted by climate change. As such, each country profile provides a readily understandable picture of both the current situation (e.g. how species-rich areas are represented in current protected areas networks) as well as that of possibilities of the future (e.g. which parts of a country are most vulnerable to potential changes in temperature or precipitation patterns). For that reason as well, interpretations of the data presented are not provided to allow readers to interpret for themselves the data.

While the majority of the country profile graphics are maps, for each country capital, anomalies in precipitation and temperature are also presented, based on the high-resolution downscaled data provided by WorldClim. These graphics demonstrate the similarities and differences among different climate change scenarios and global climate models, through basic statistics regarding the variety of outputs given by the climate change scenarios for each national capital.

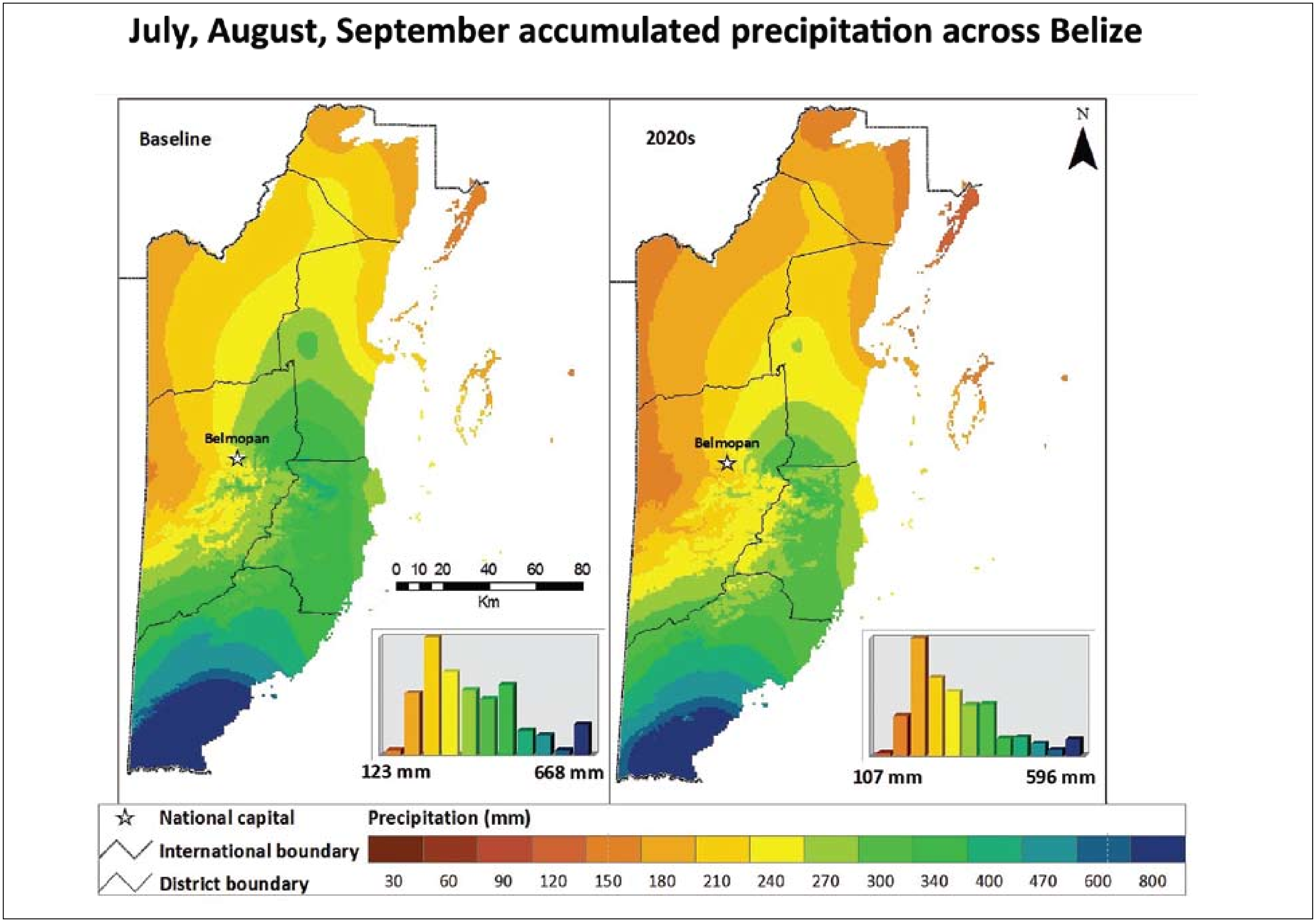
It is worth noting that given the emission scenarios supplied by the IPCC, the temperature is almost always projected to be lower in the B2 scenario than in the A2 scenario. In terms of temperature, there is not high variation or disagreement among the models. The different models begin to deviate from each other further into the future. Precipitation projections range greatly, both in the next decade as well as in the furthest projections. One general trend evident in the Mesoamerican analyses performed here is that there is a commonly projected drying of the wet season. There are not enough sample points in the Caribbean to make such a generalization. Overall, precipitation is much more difficult to model than temperature.

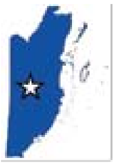
The six lines represent the A2 and B2 scenario runs from the United Kingdom’s Hadley Centre Coupled Model, version 3 (HADCM3), the Canadian Centre for Climate Modelling and Analysis’ Coupled Global Climate Model (CGCM3T47), and Australia’s Commonwealth Scientific and Industrial Research Organisation coupled model (CSIRO Mk3).


Species Richness:Belize
N
Protected areas
Species richness
543 species
17 species
0
10
20
40
60
80
km

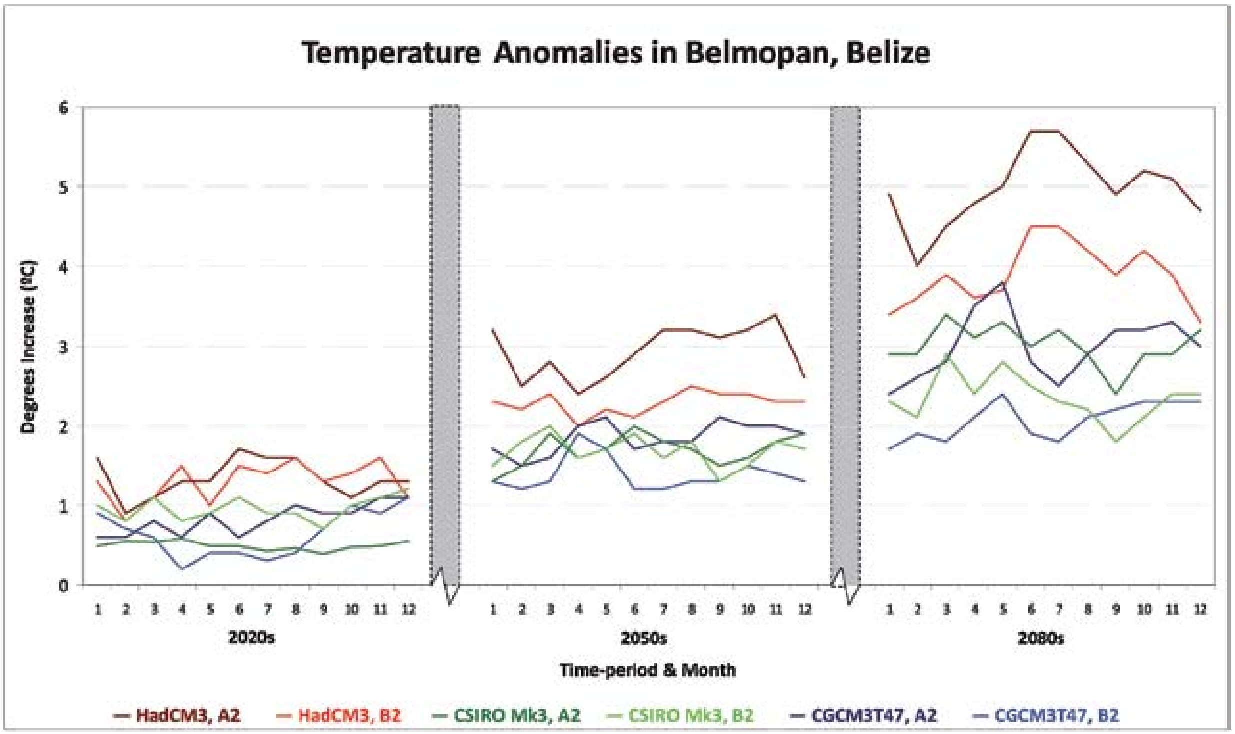


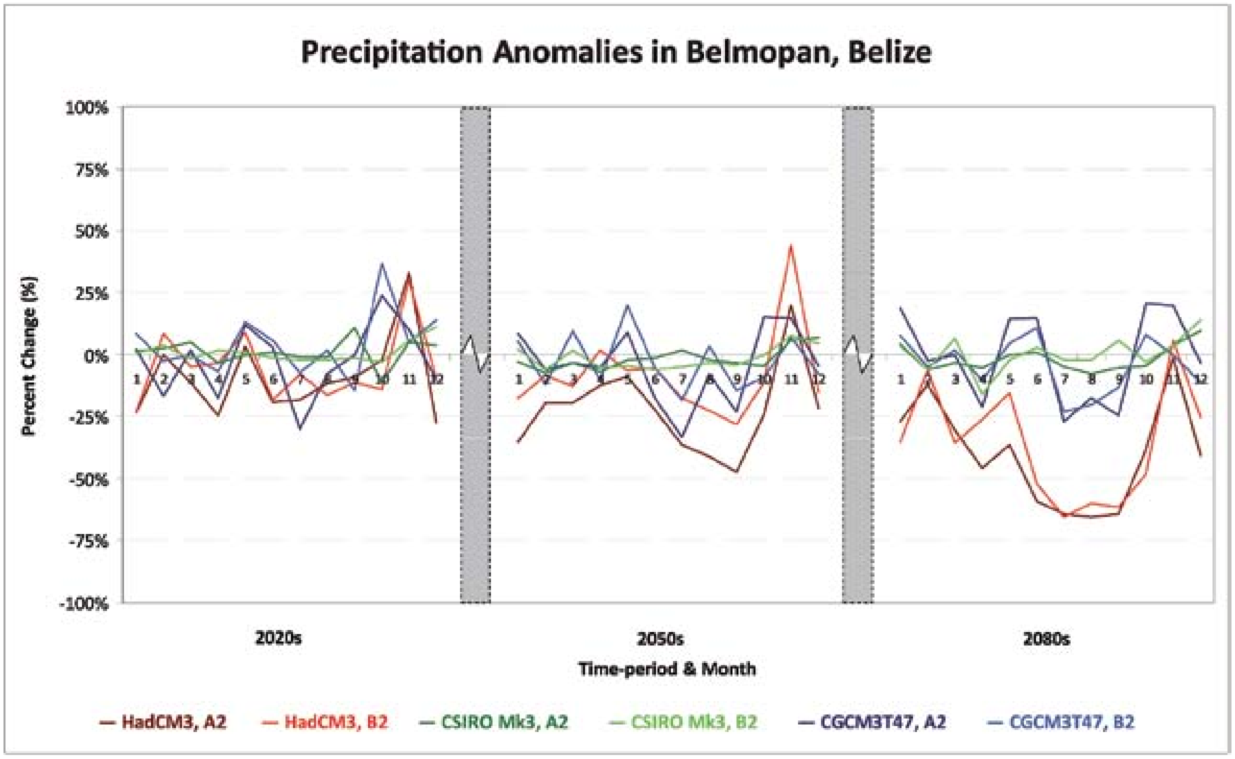
Average July Temperature across Belize


July, August, September accumulated precipitation across Belize

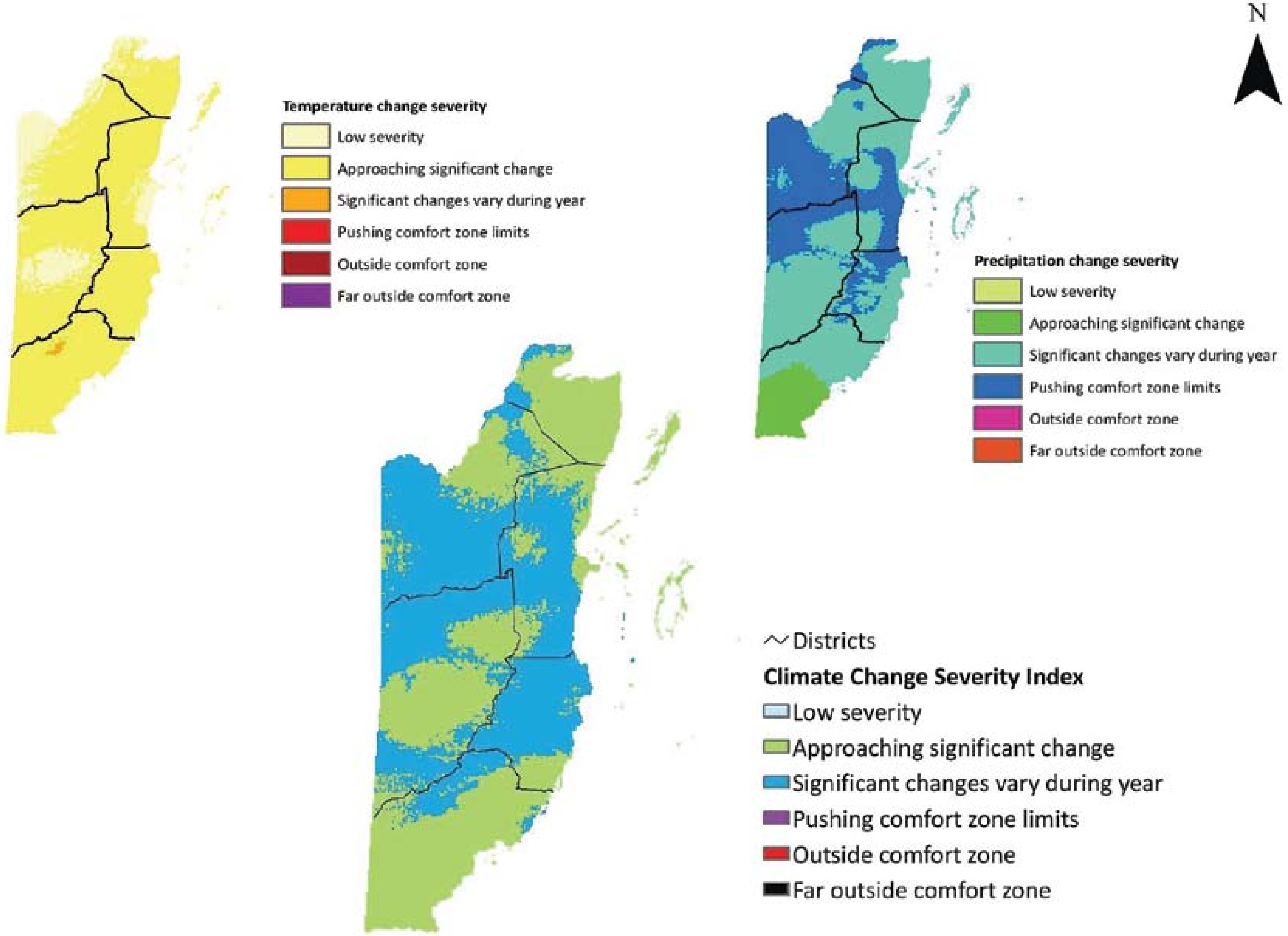


Belmopan, Belize

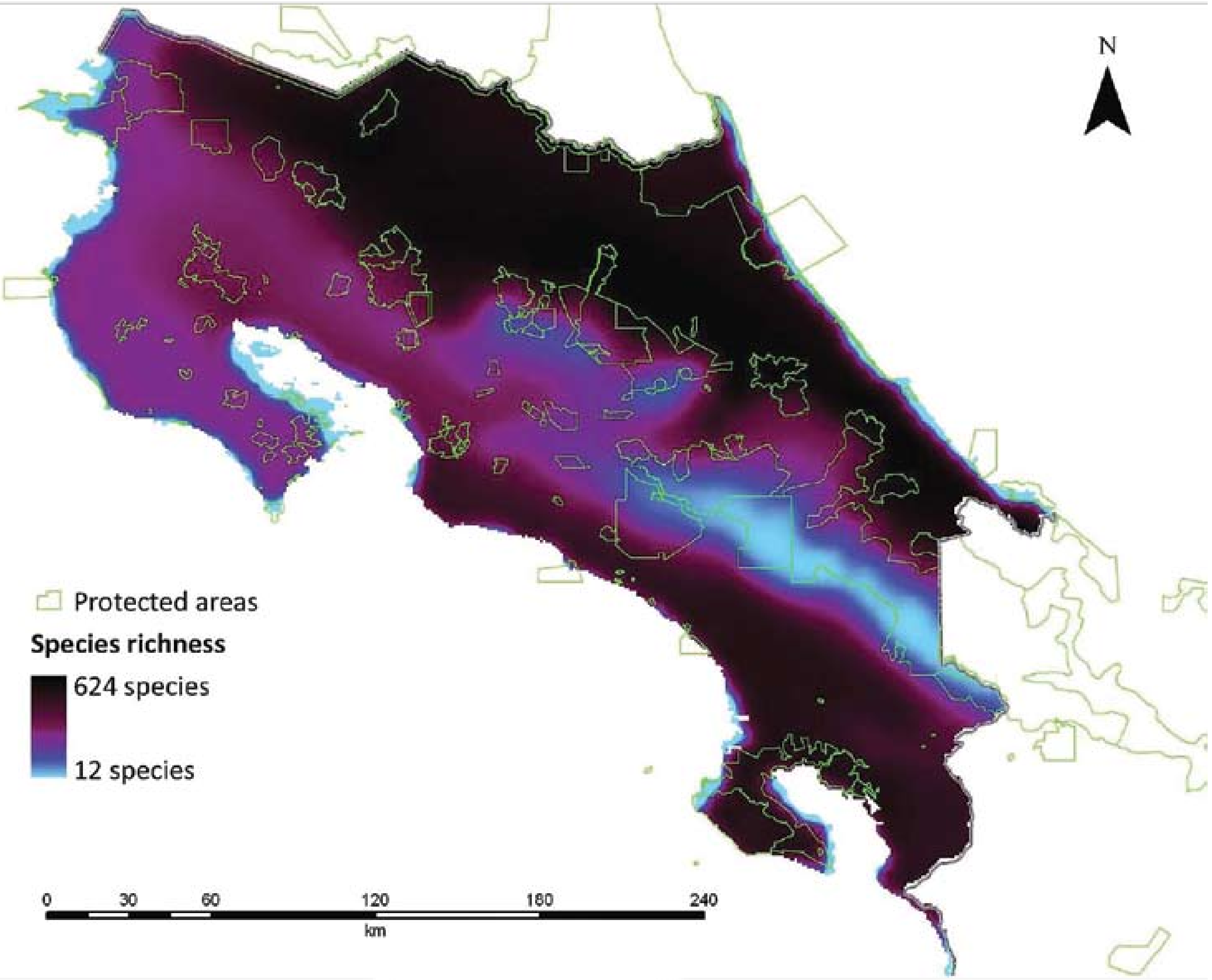


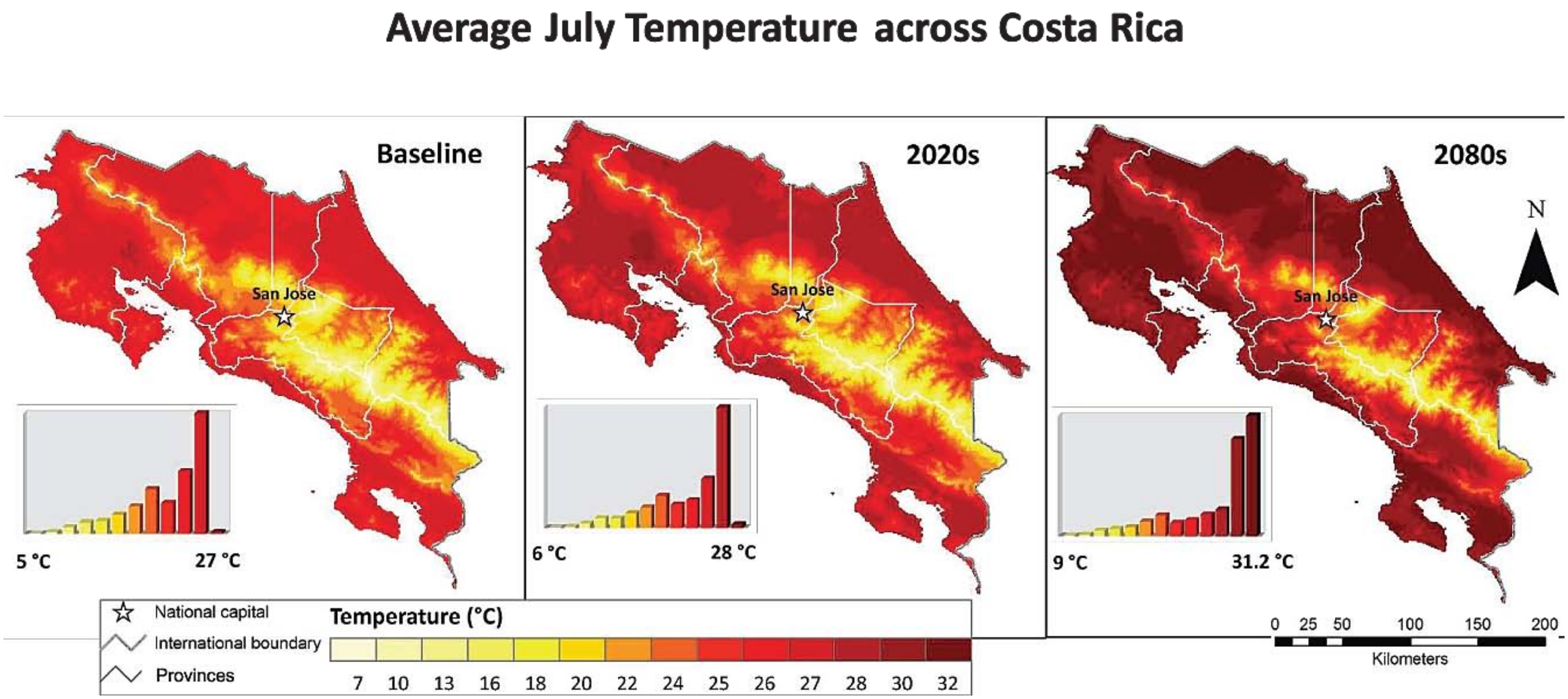


Climate Change Severity Index for Belize (towards the 2020s)

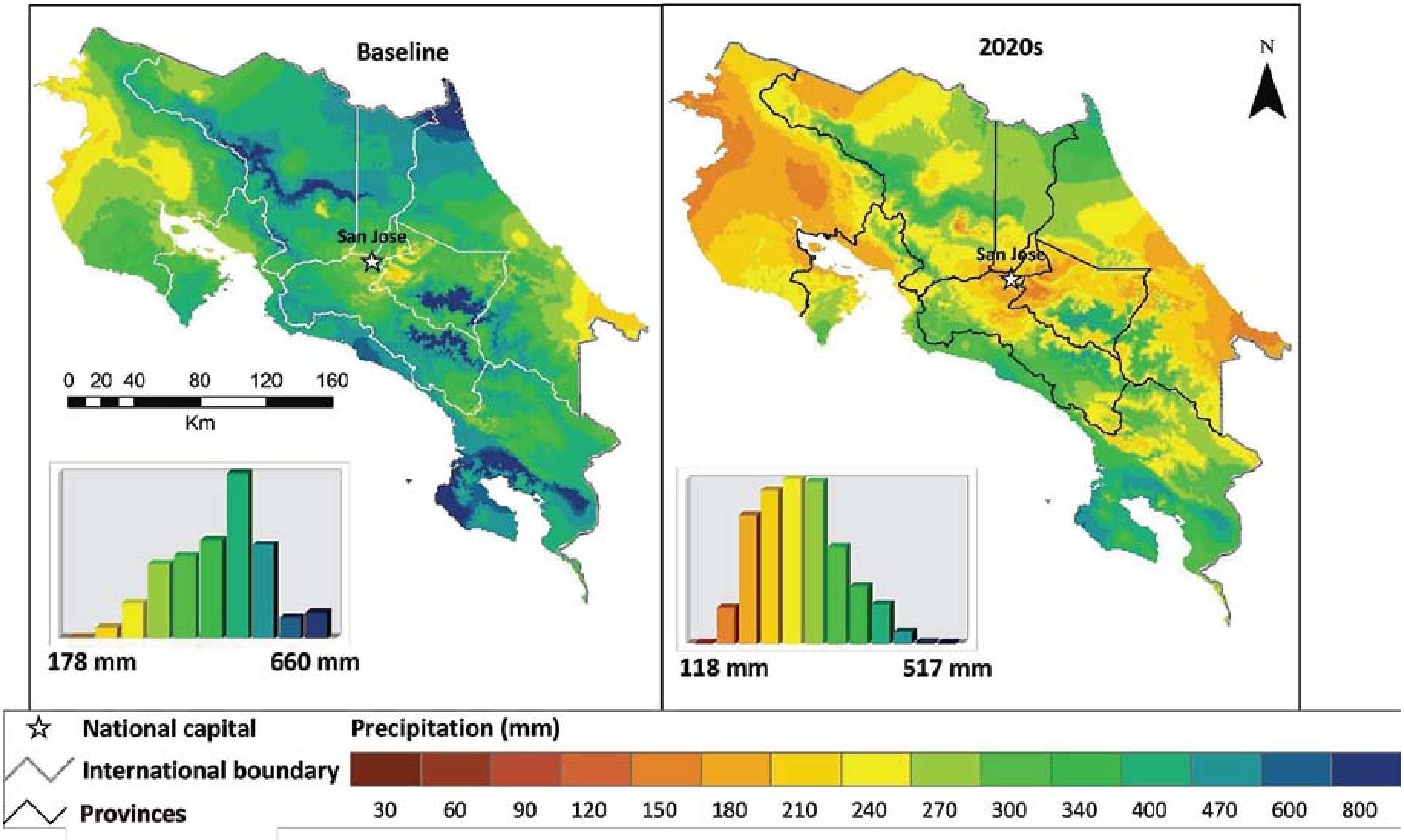


Species Richness: Costa Rica

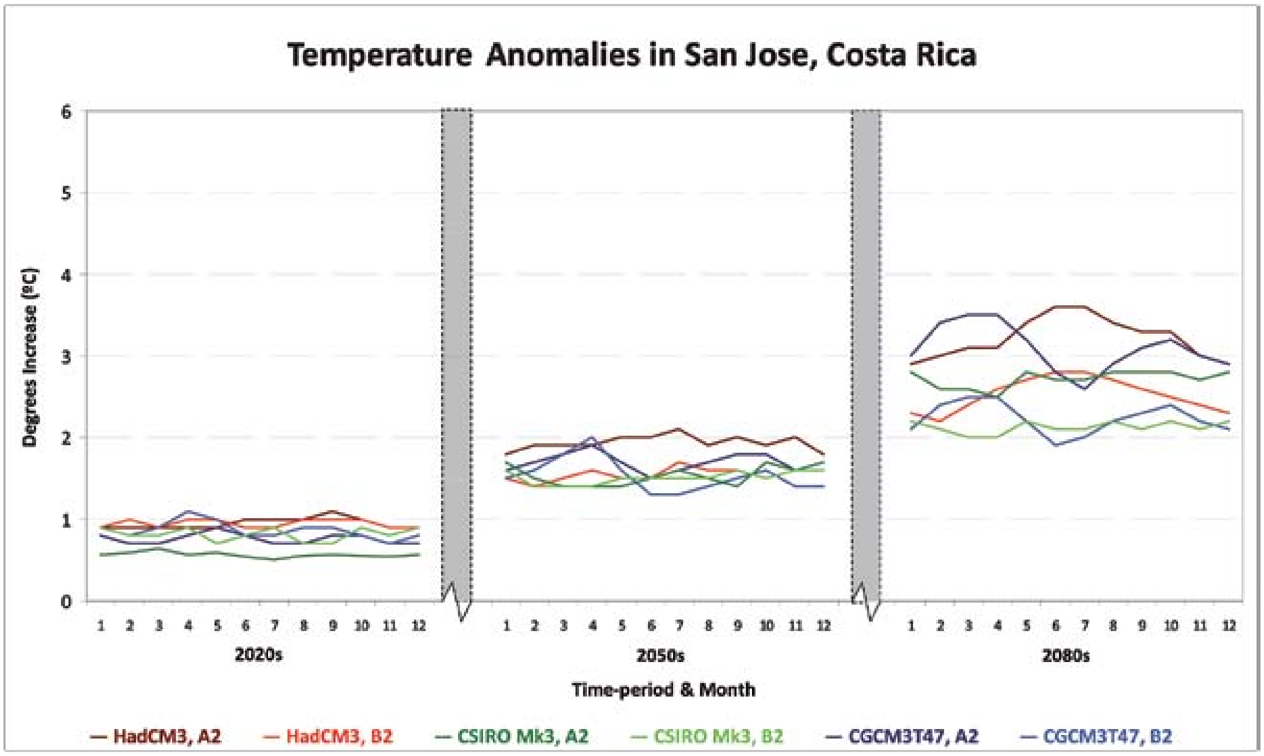



Average July Temperature across Costa Rica
Baseline
San Jose
5 °C
27 °C
2020s
San Jose
6 °C
28 °C
2080s
San Jose
9 °C
31.2 °C
N
☆ National capital
International boundary
Provinces
Temperature (°C)
7 10 13 16 18 20 22 24 25 26 27 28 30 32
0 25 50 100 150 200
Kilometers

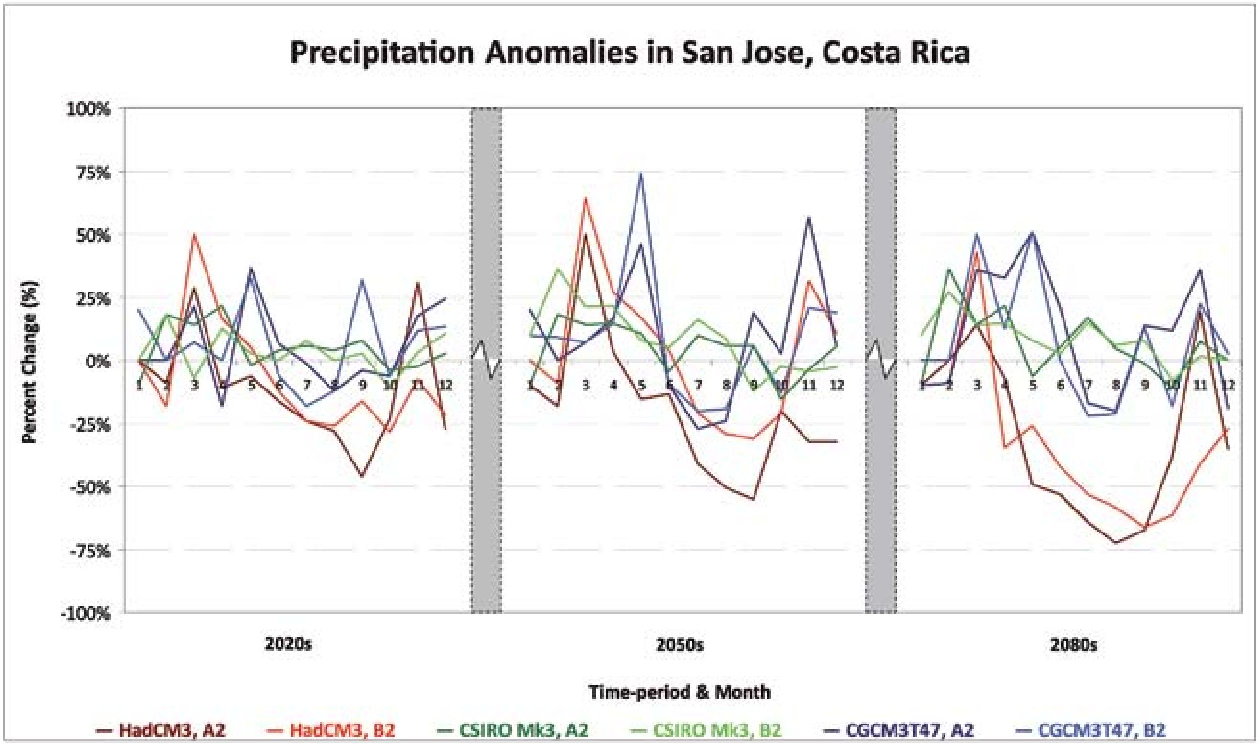
July, August, September accumulated precipitation across Costa Rica



San Jose, Costa Rica

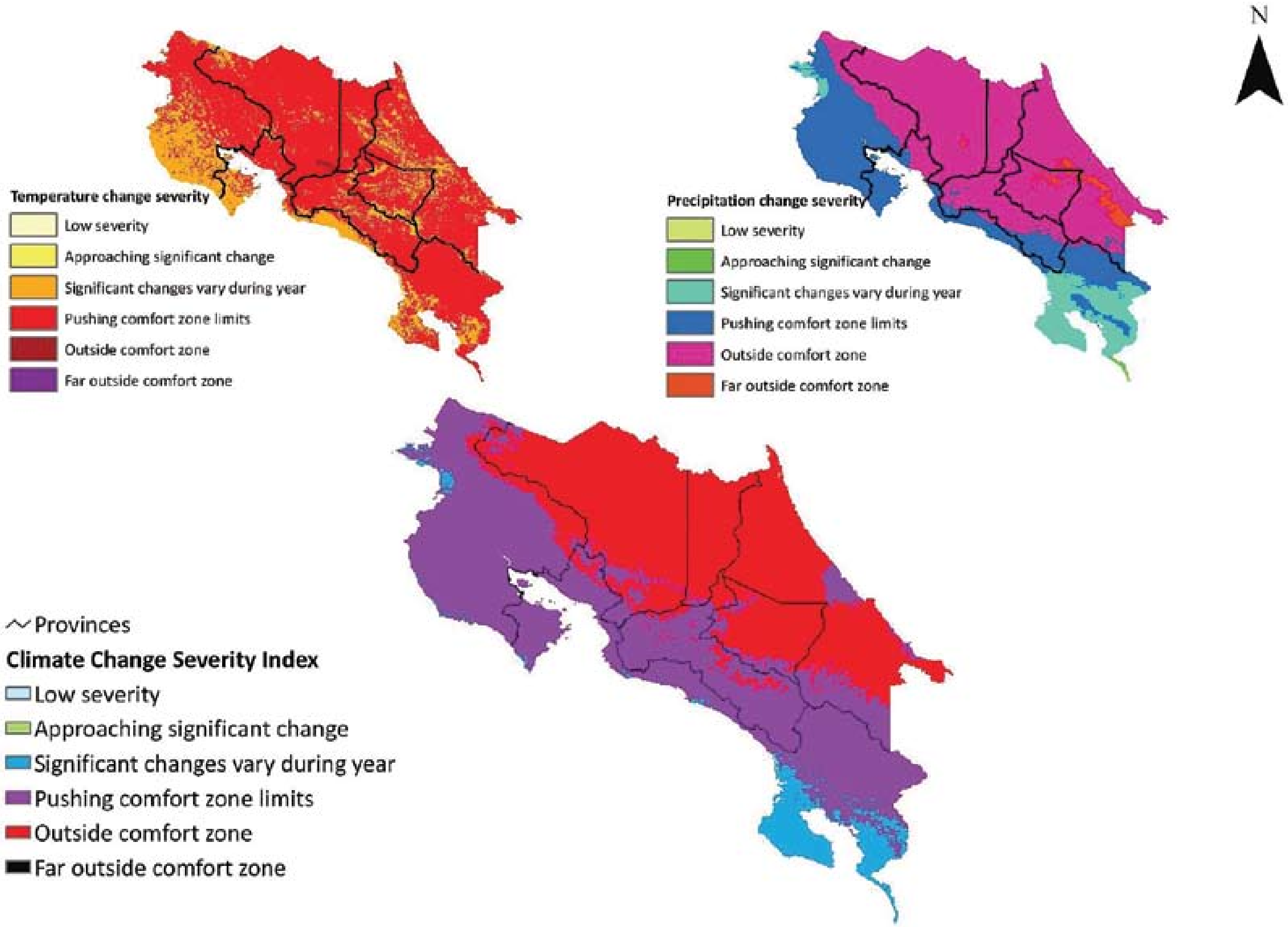


Temperature Anomalies in San Jose, Costa Rica

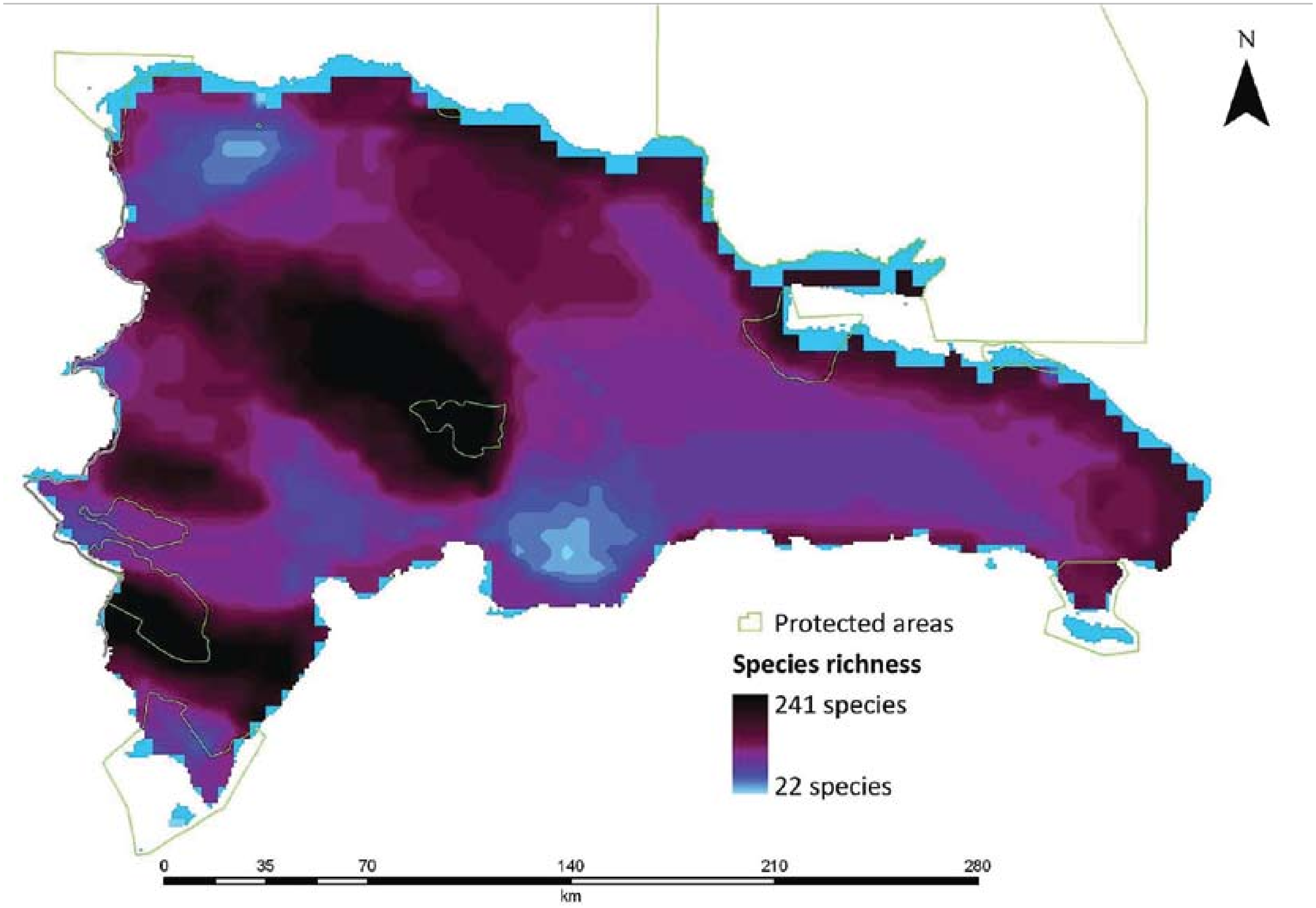


Precipitation Anomalies in San Jose, Costa Rica

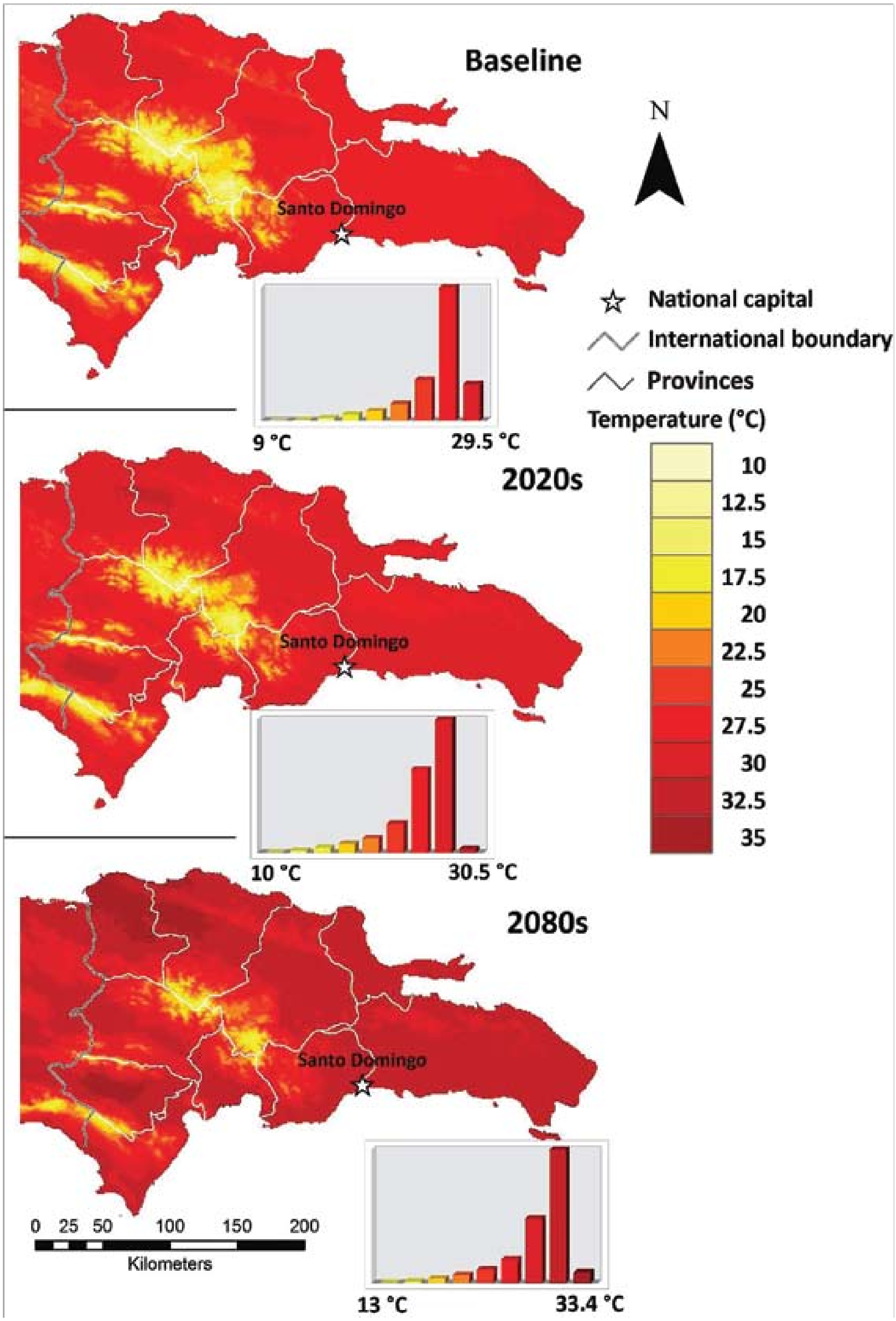
Climate Change Severity Index for Costa Rica (towards the 2020s)

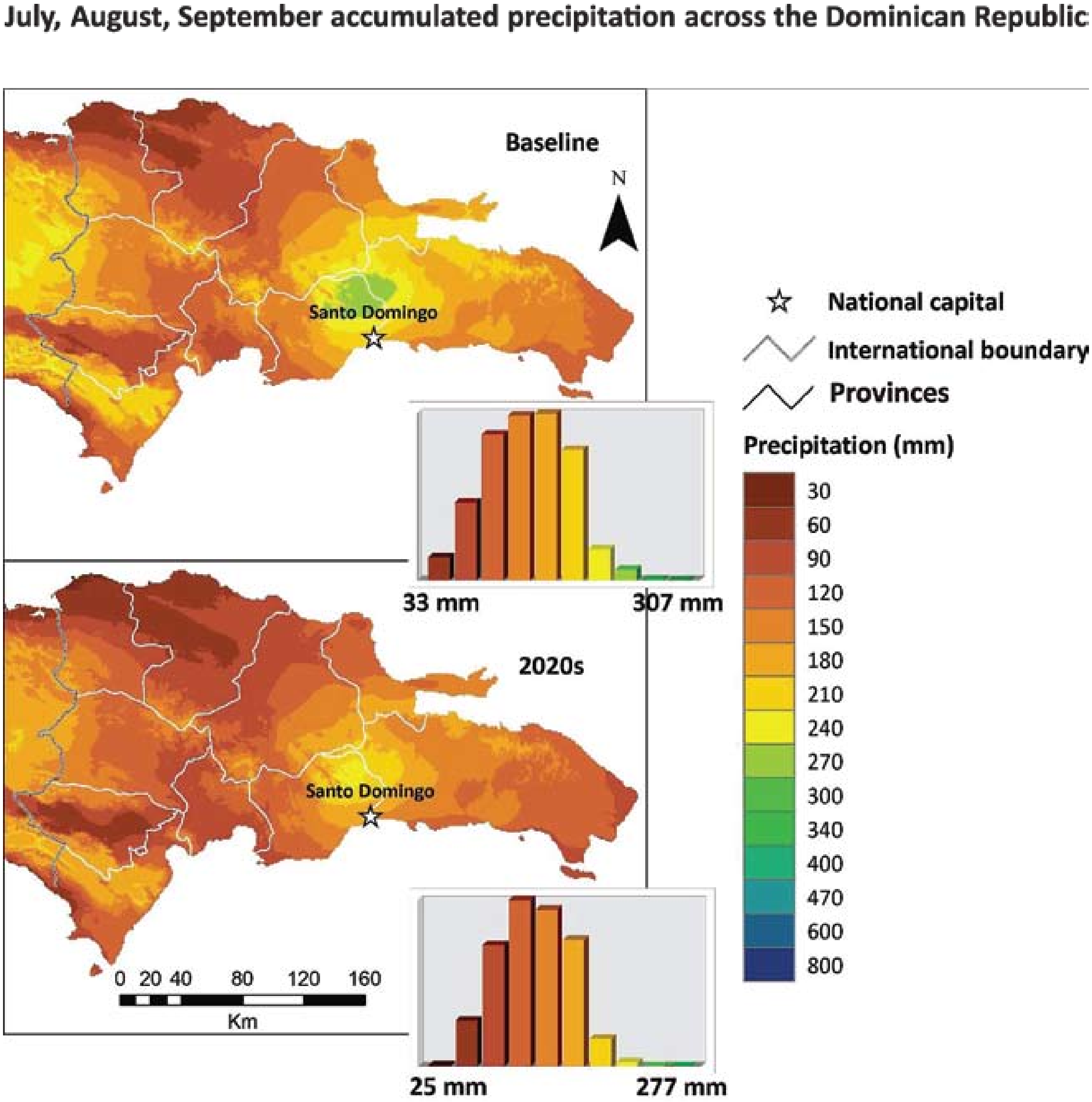


Species Richness: the Dominican Republic

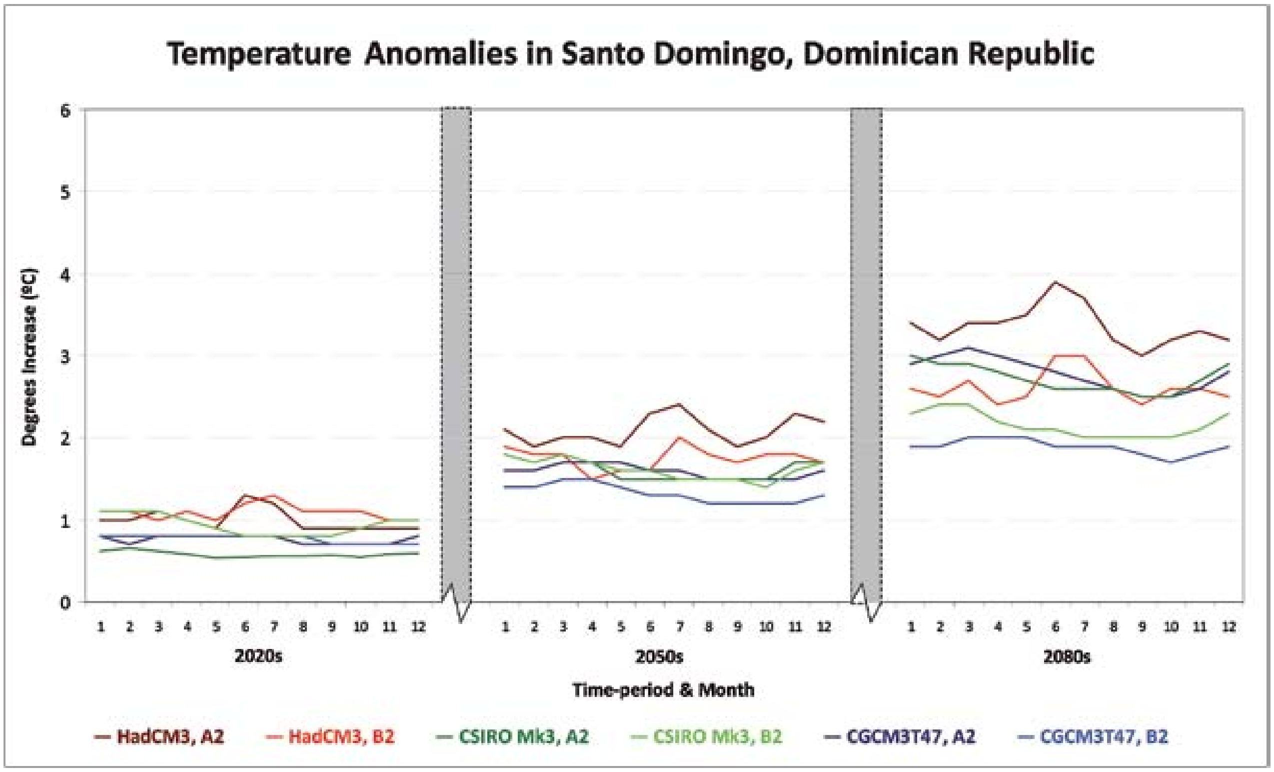


Average July Temperature across the Dominican Republic

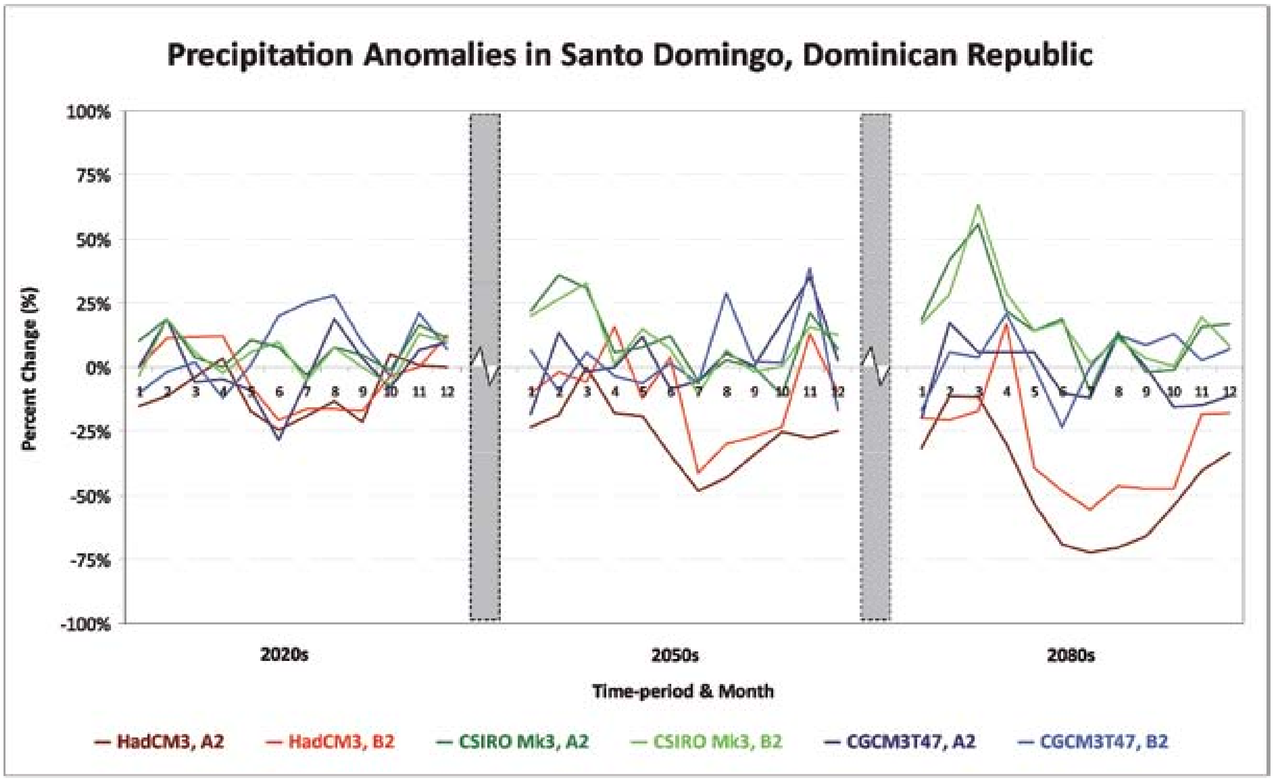



July, August, September accumulated precipitation across the Dominican Republic
Baseline
N
Santo Domingo
33 mm
307 mm
2020s
Santo Domingo
0 20 40 80 120 160
Km
25 mm
277 mm
National capital
International boundary
Provinces
Precipitation (mm)
30
60
90
120
150
180
210
240
270
300
340
400
470
600
800

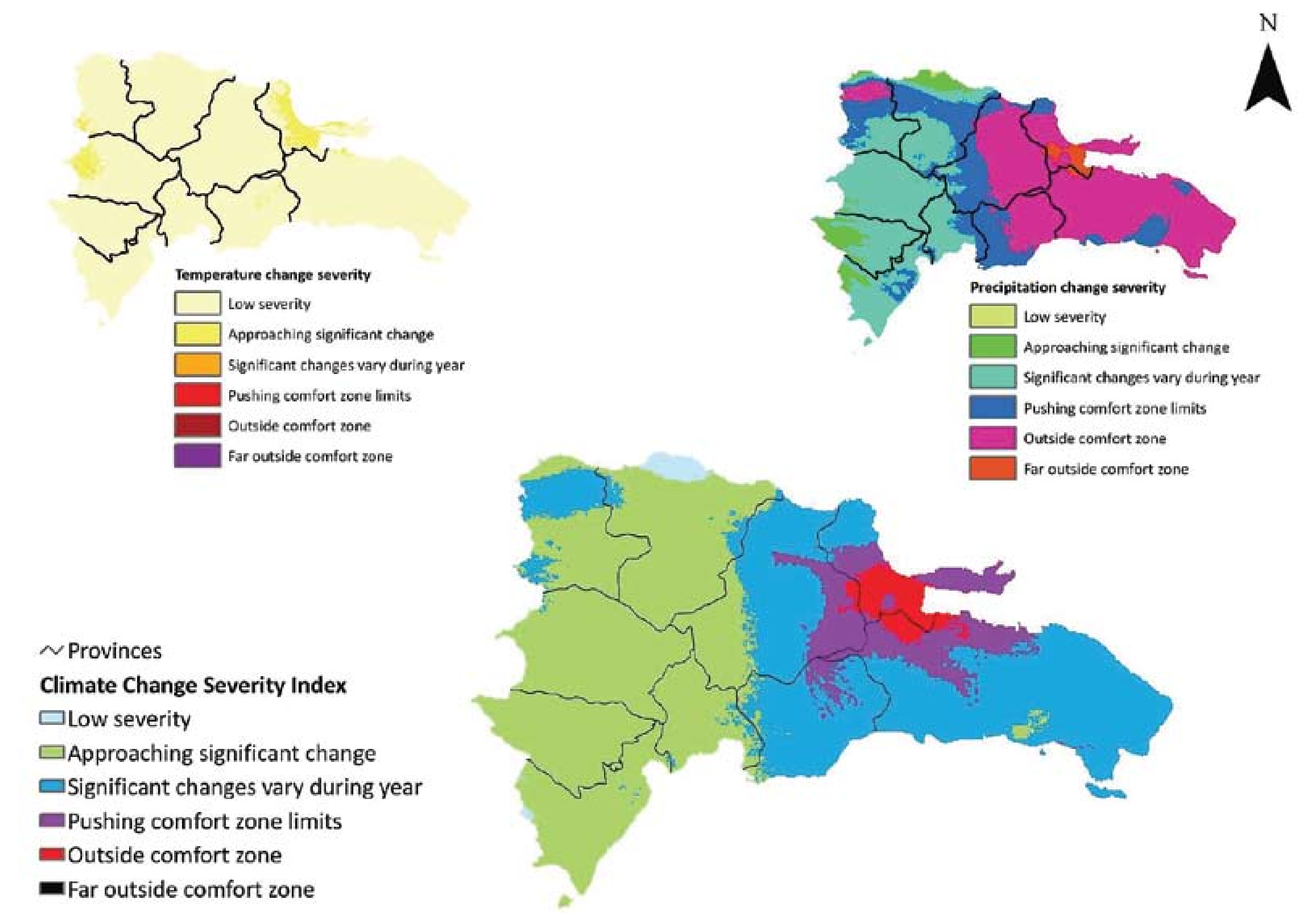
Santo Domingo, Dominican Republic



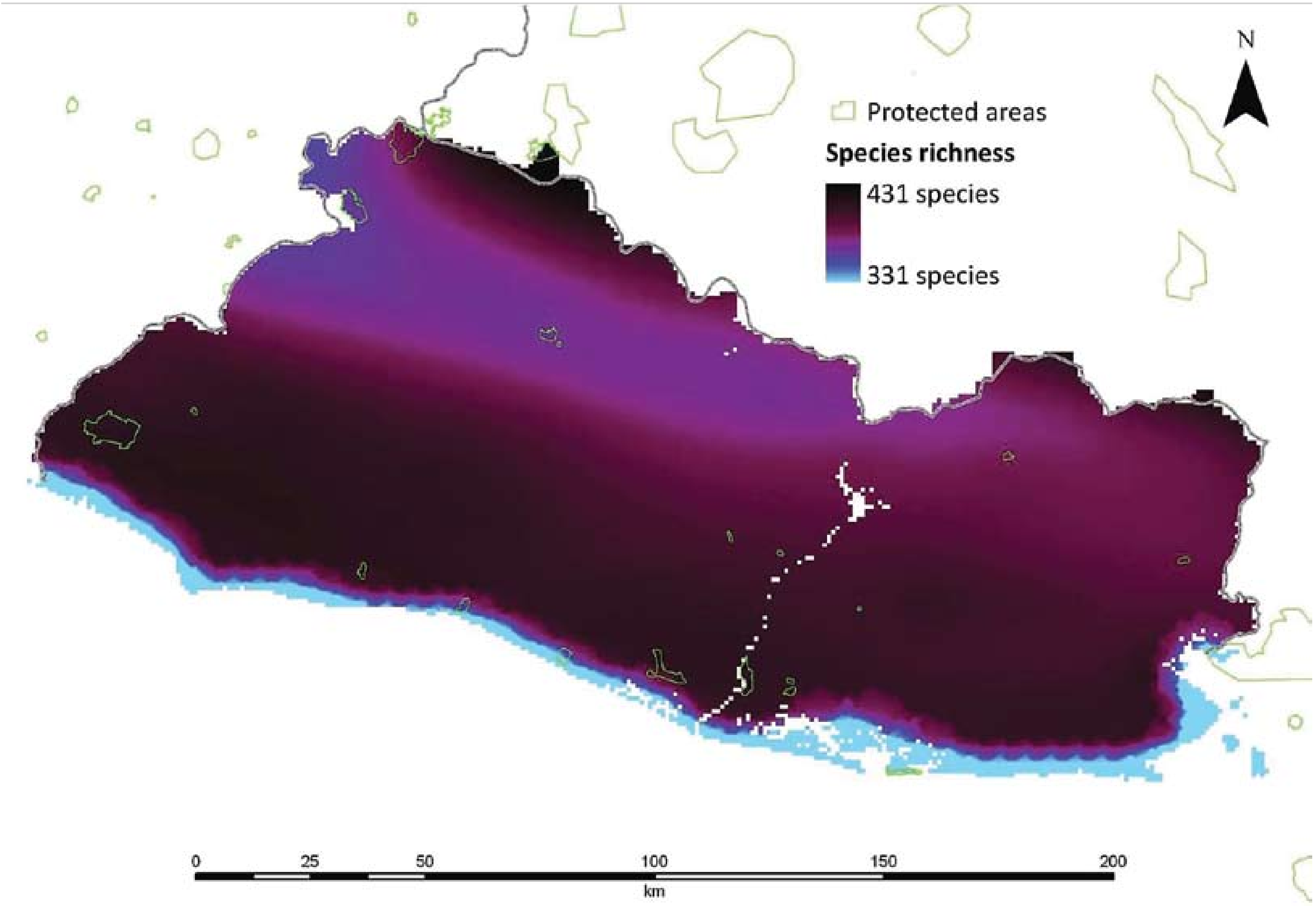
Temperature Anomalies in Santo Domingo, Dominican Republic



Precipitation Anomalies in Santo Domingo, Dominican Republic

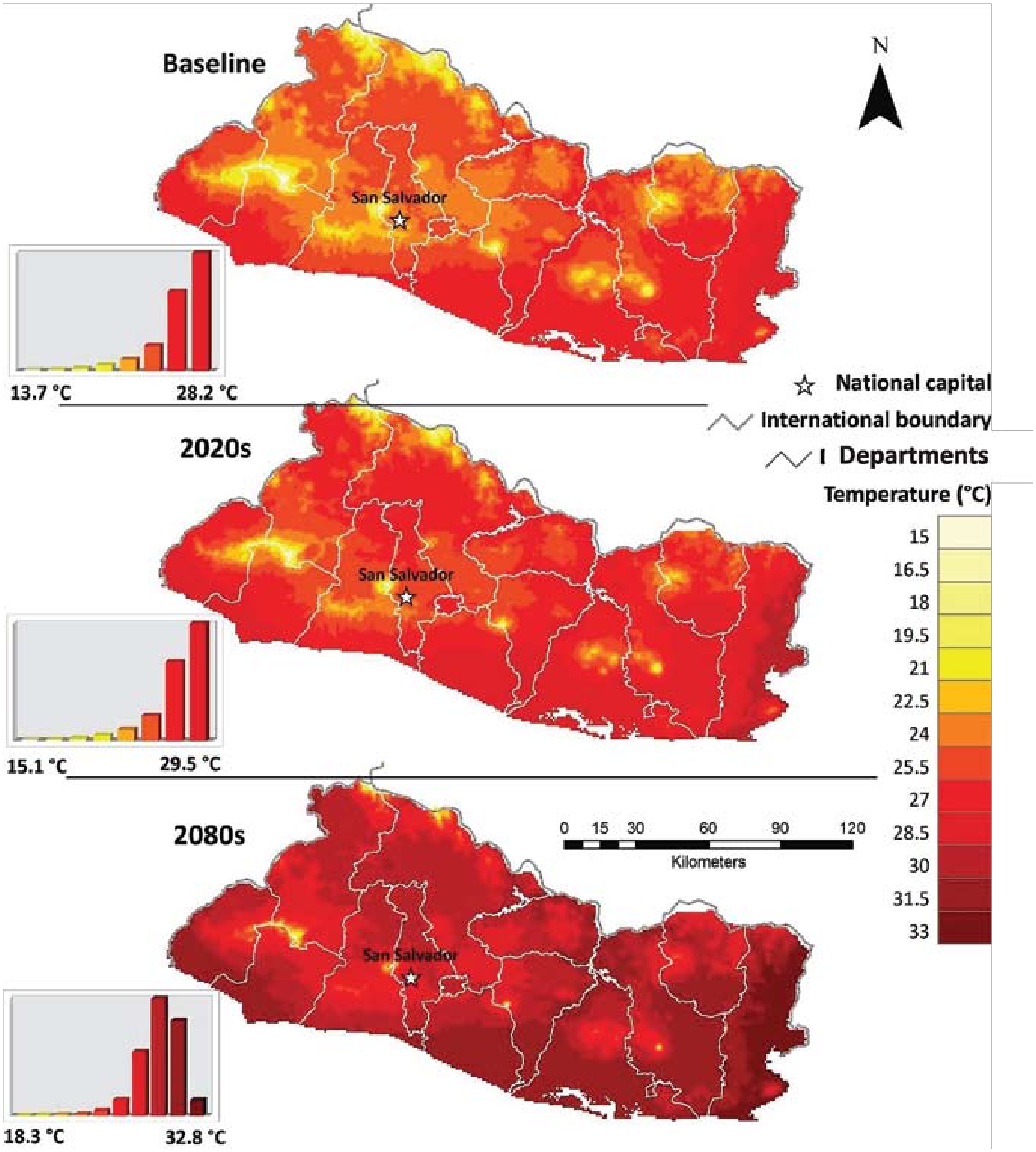


Climate Change Severity Index for the Dominican Republic (towards the 2020s)

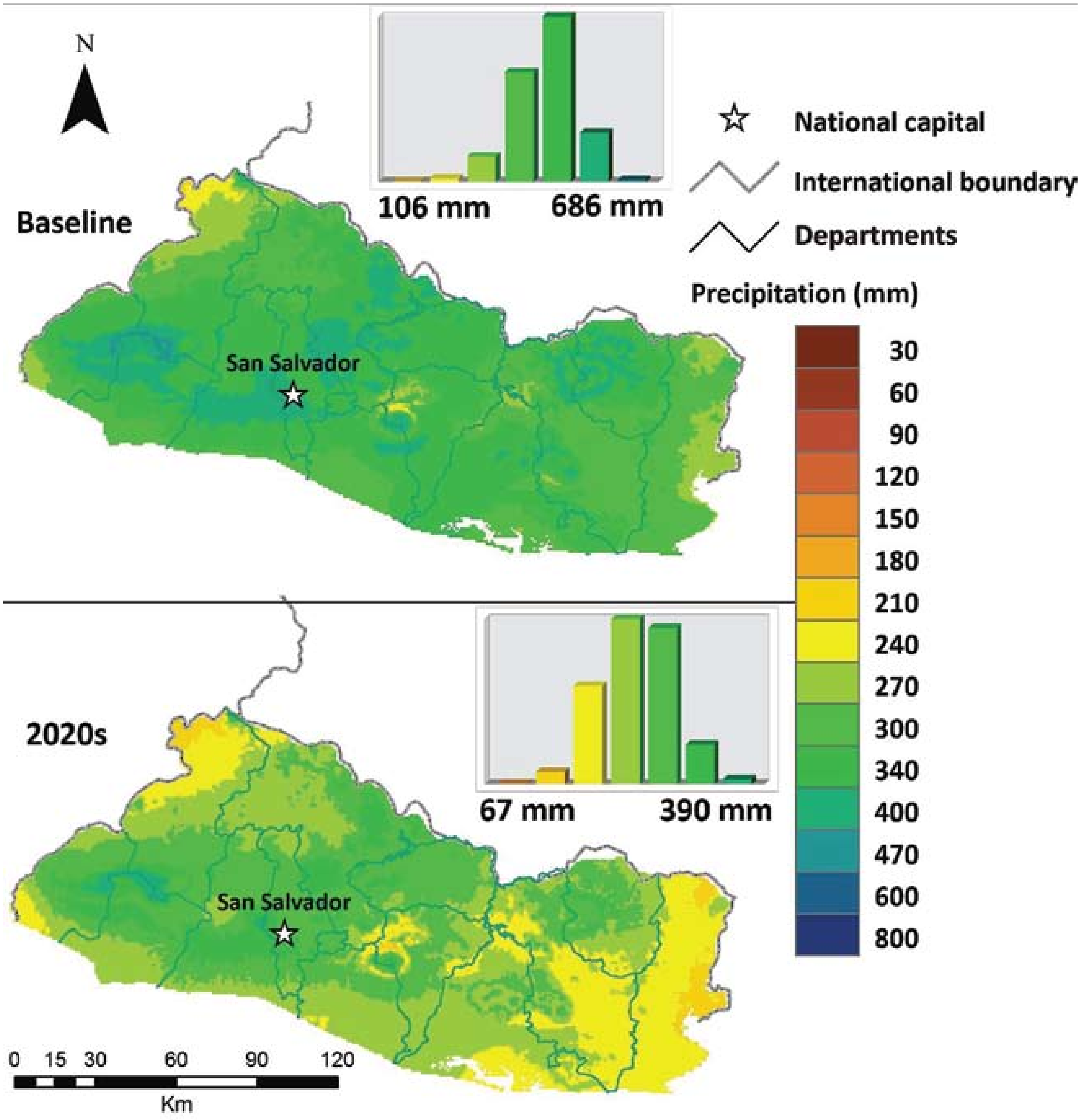


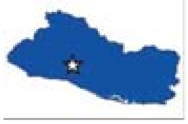
Species Richness: El Salvador

Average July Temperature across El Salvador

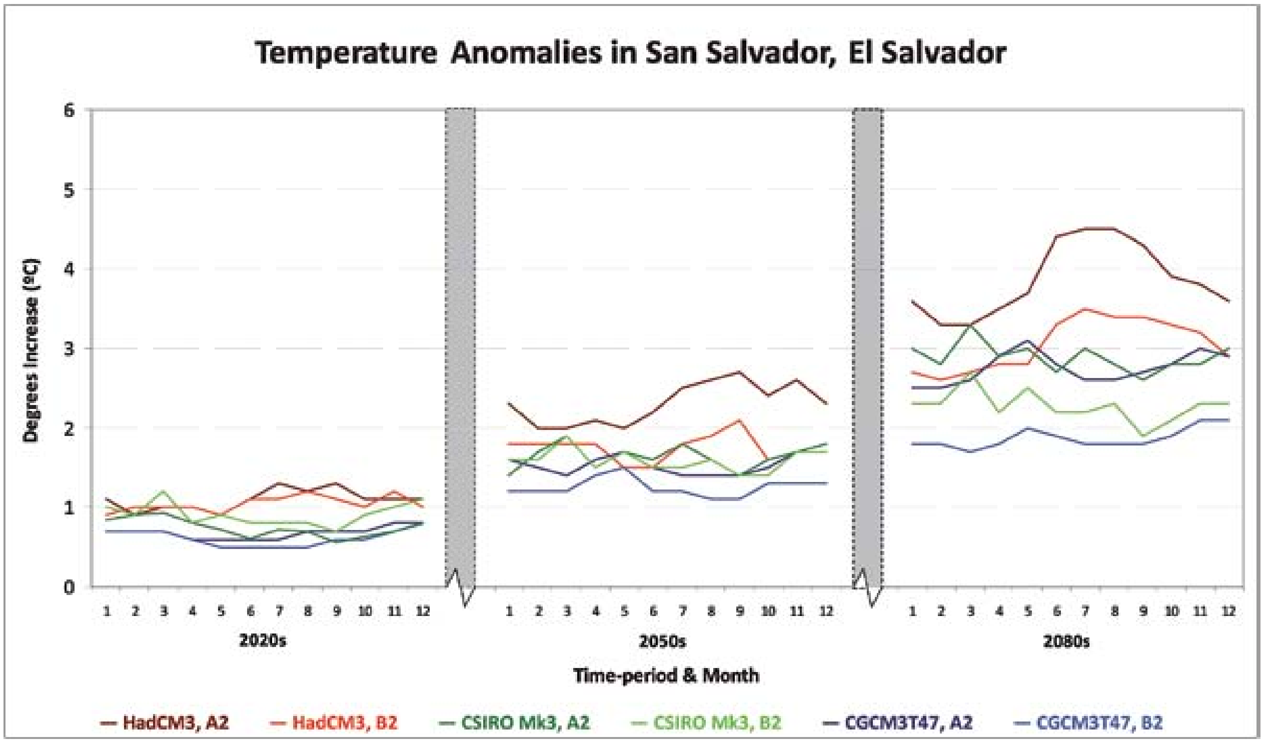


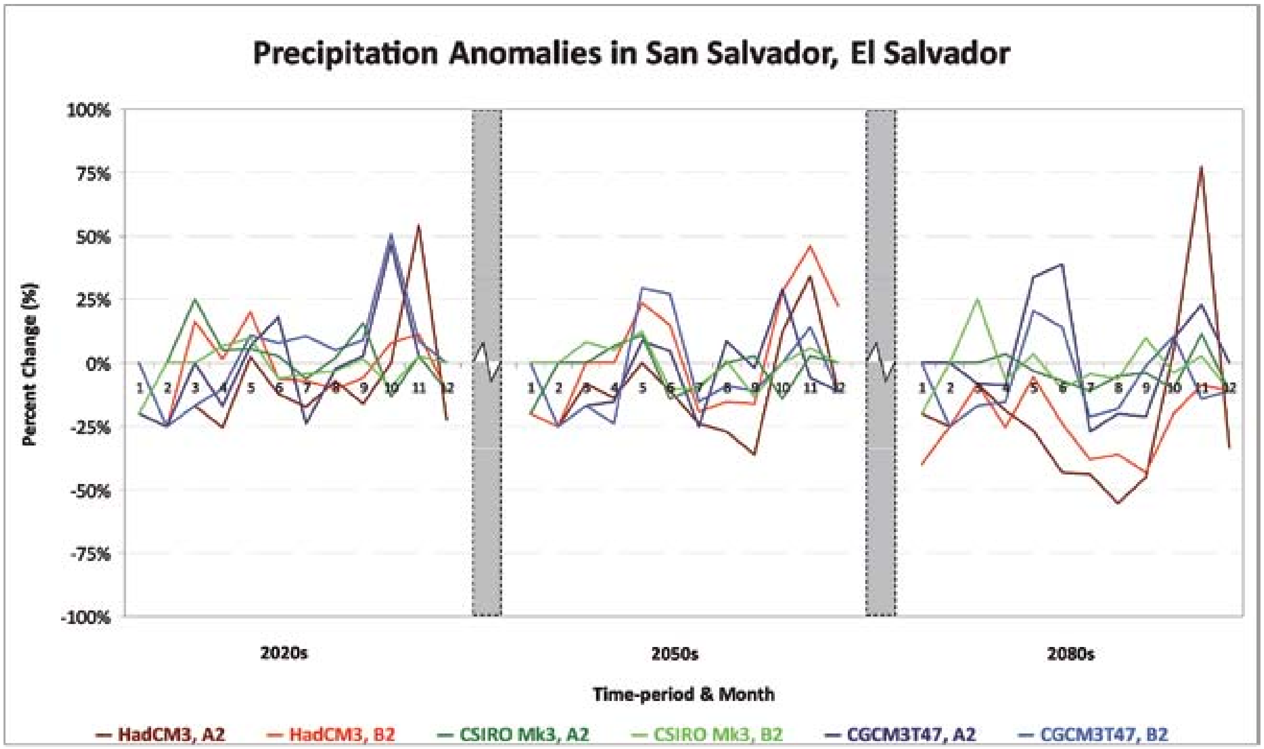
July, August, September accumulated precipitation across El Salvador

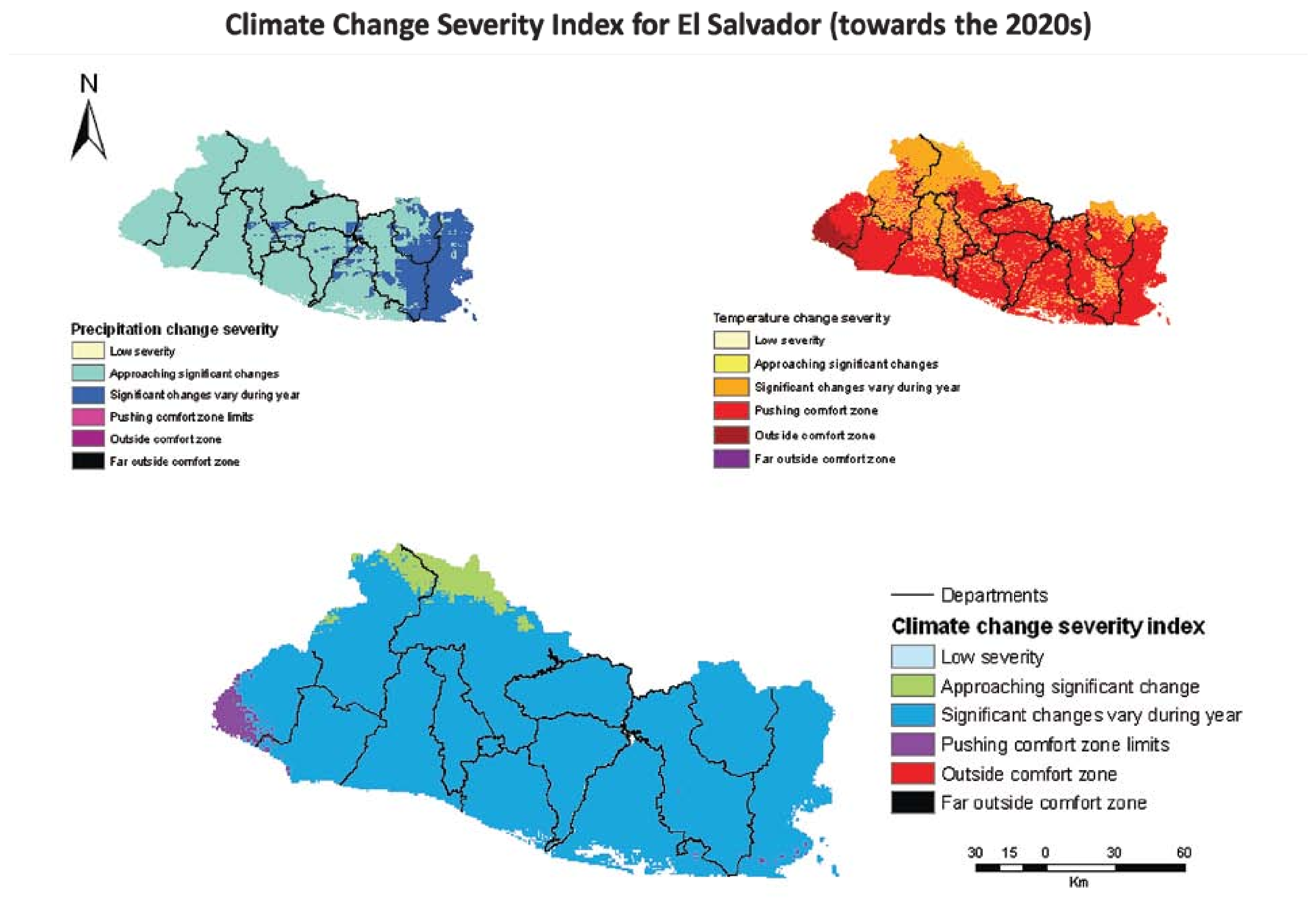




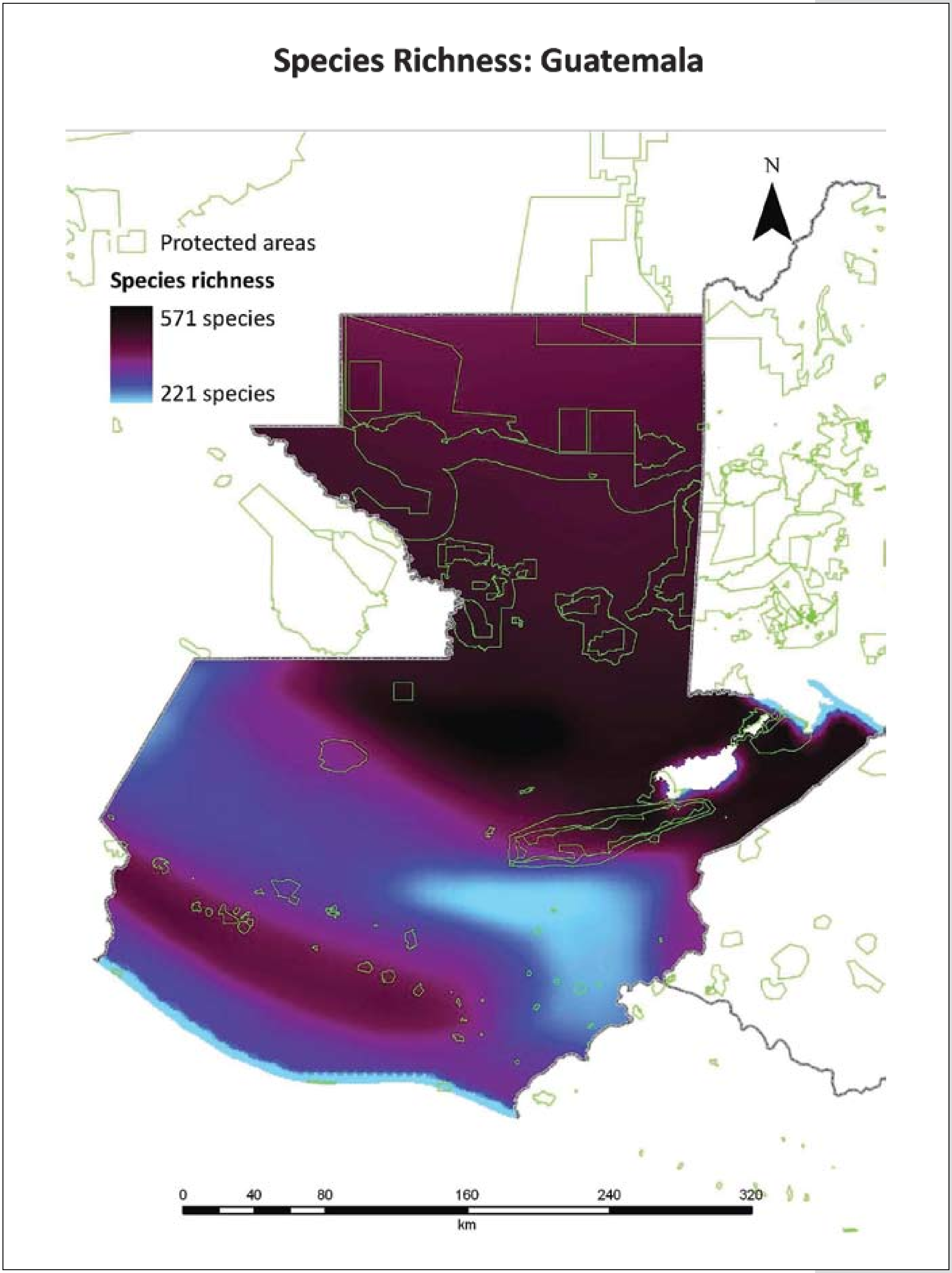
San Salvador, El Salvador

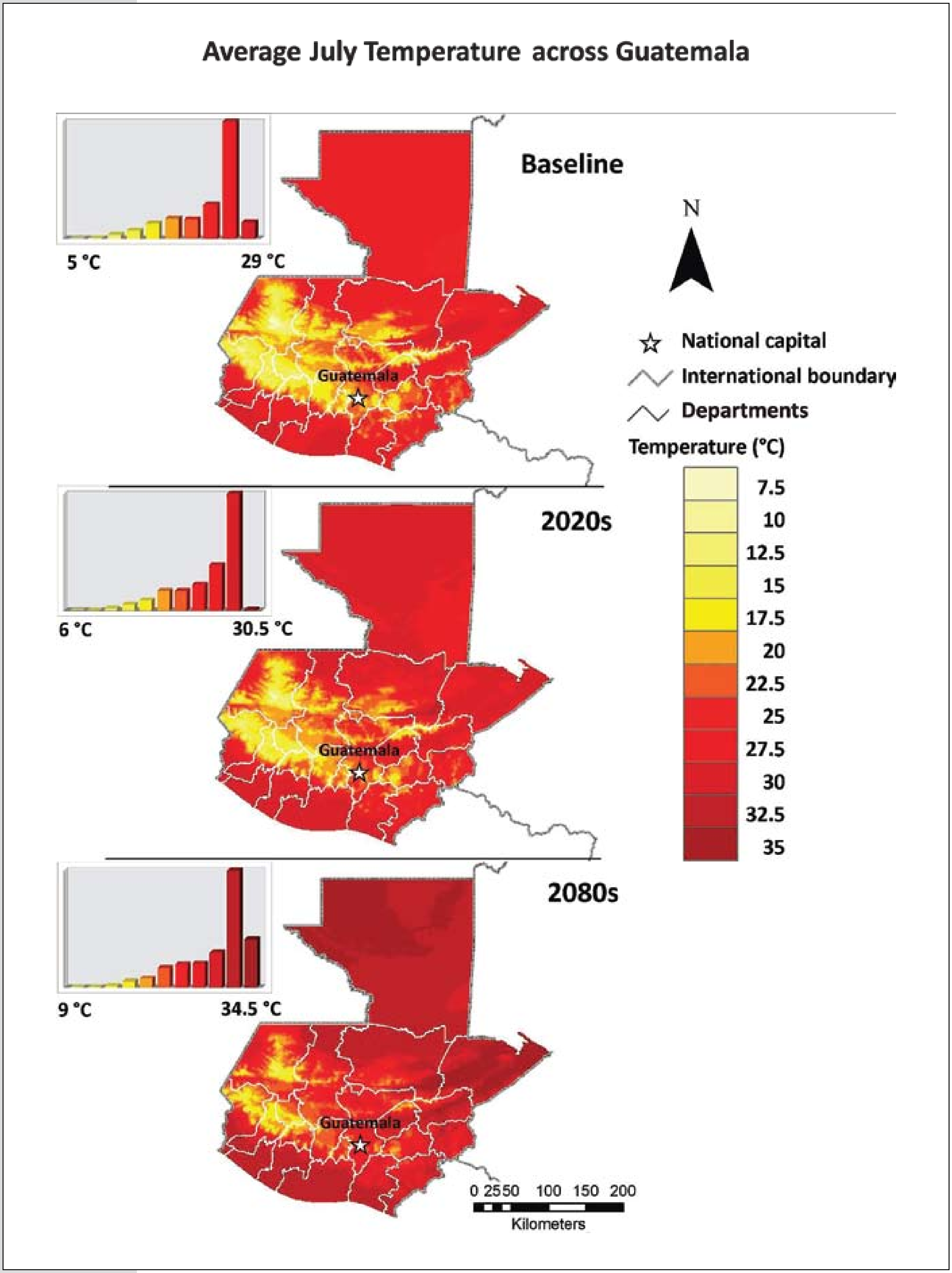




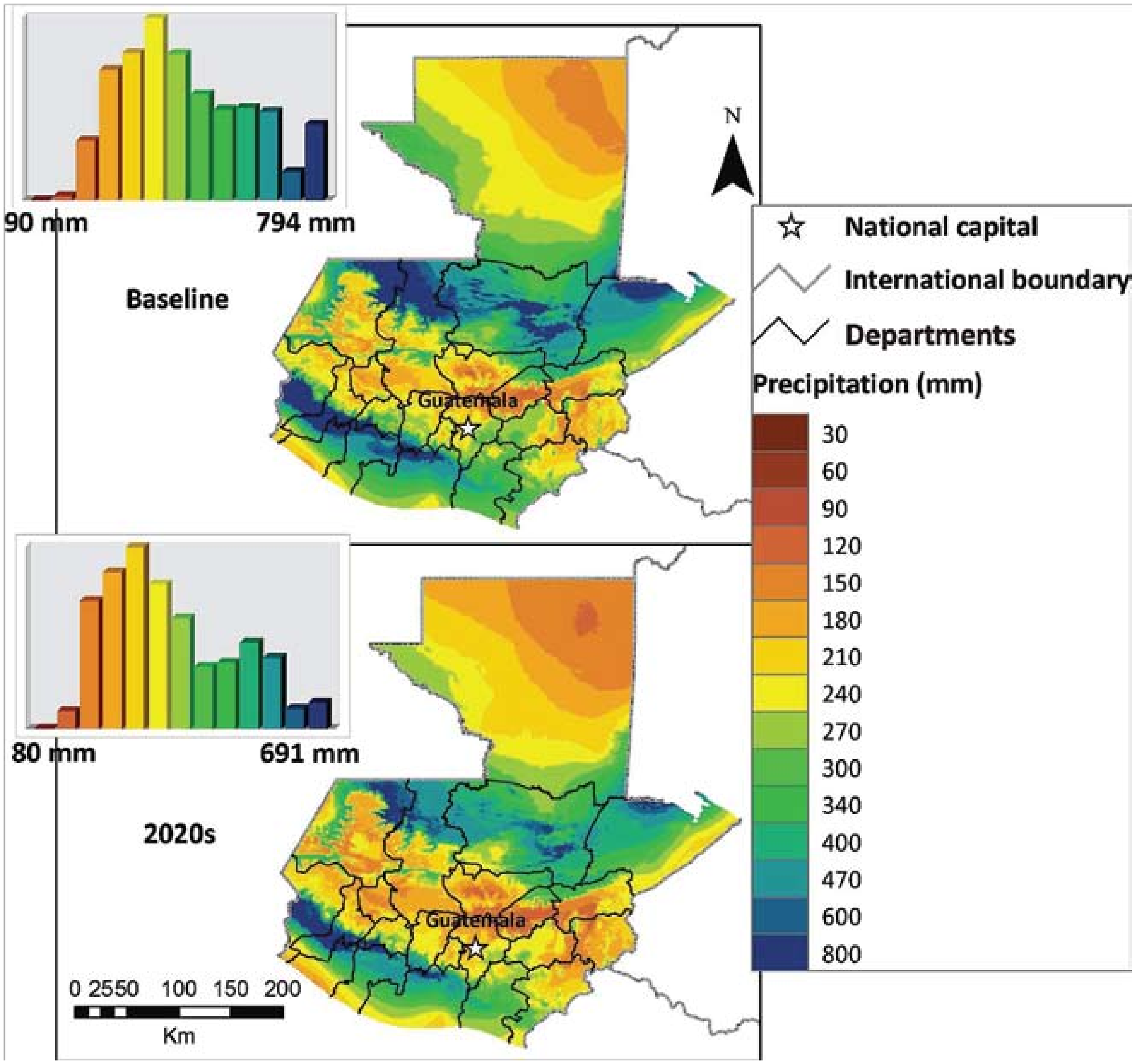


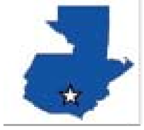
Climate Change Severity Index for El Salvador (towards the 2020s)


Species Richness: Guatemala
N
Protected areas
Species richness
571 species
221 species
0
40
80
160
240
320
km

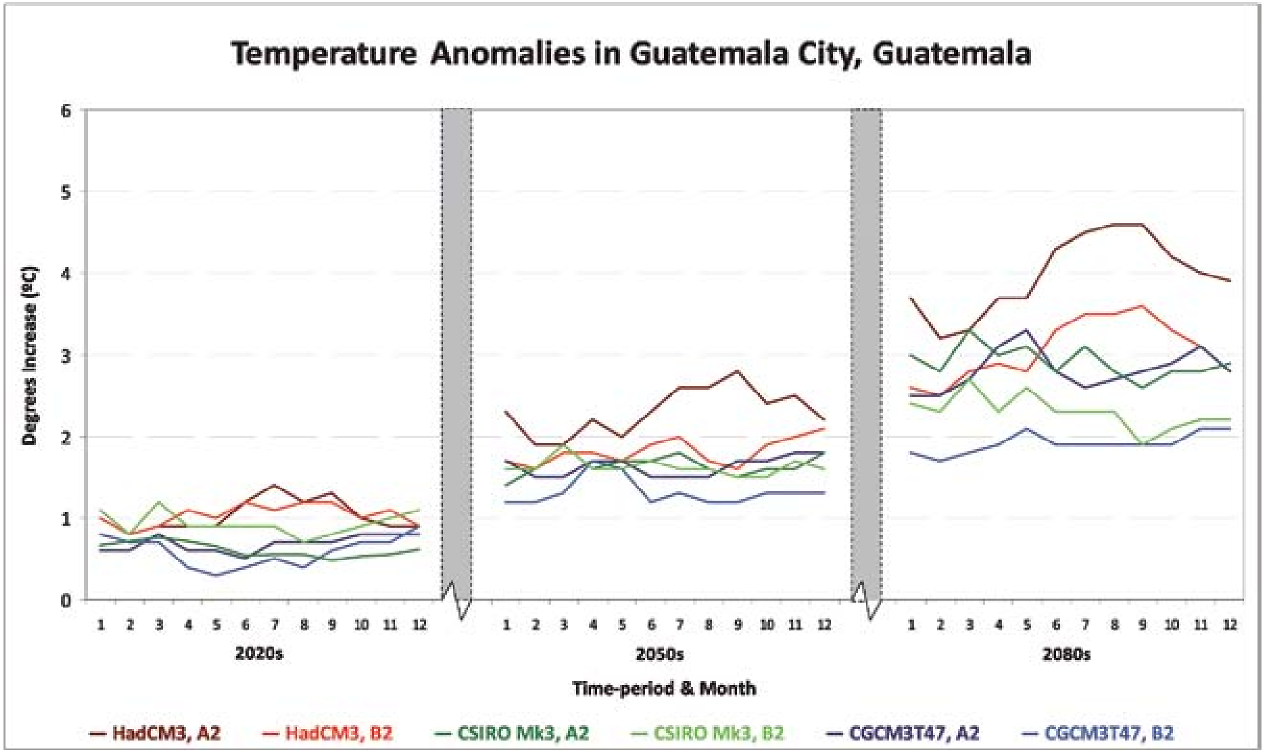

Average July Temperature across Guatemala
Baseline
5 °C
29 °C
2020s
6 °C
30.5 °C
2080s
9 °C
34.5 °C
Guatemala
N
☆ National capital
International boundary
Departments
Temperature (°C)
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
32.5
35
0 25 50 100 150 200
Kilometers

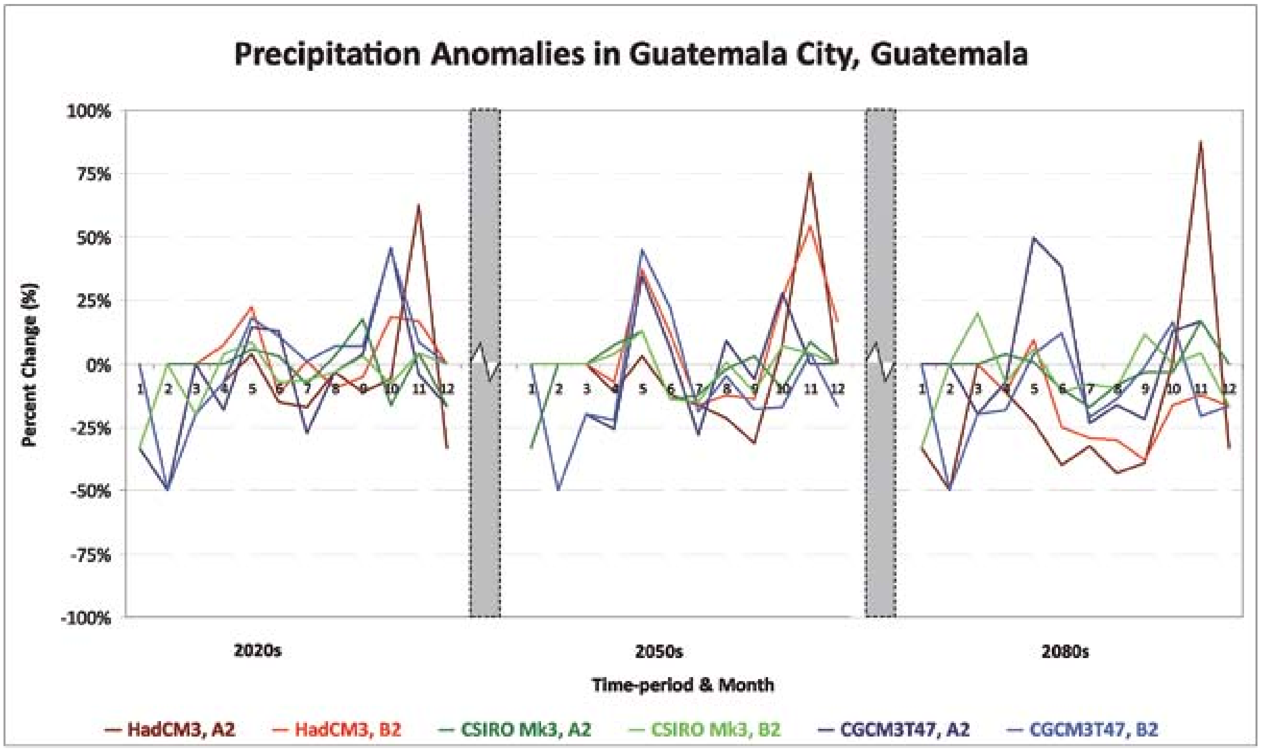
July, August, September accumulated precipitation across Guatemala



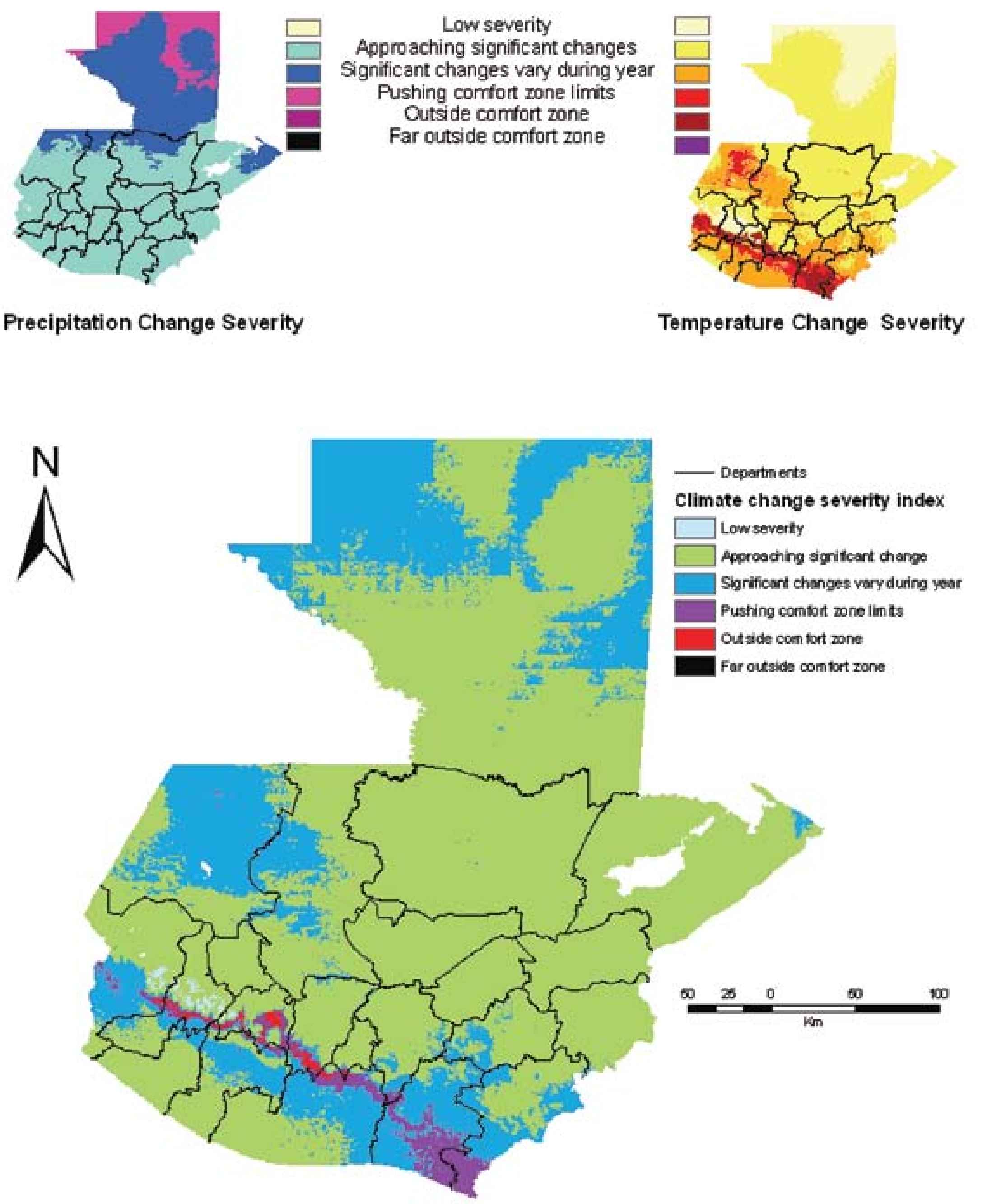


Guatemala City, Guatemala

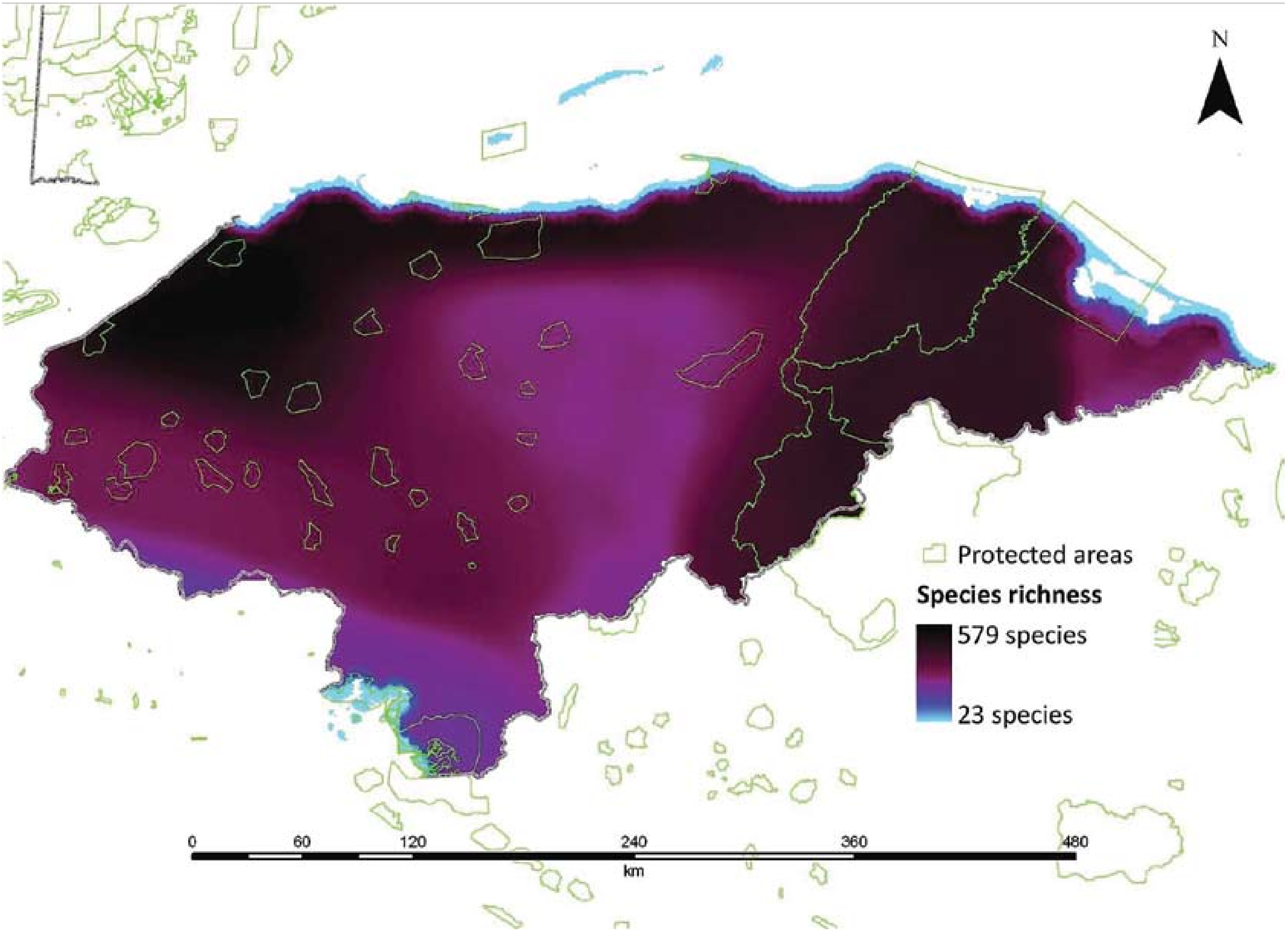


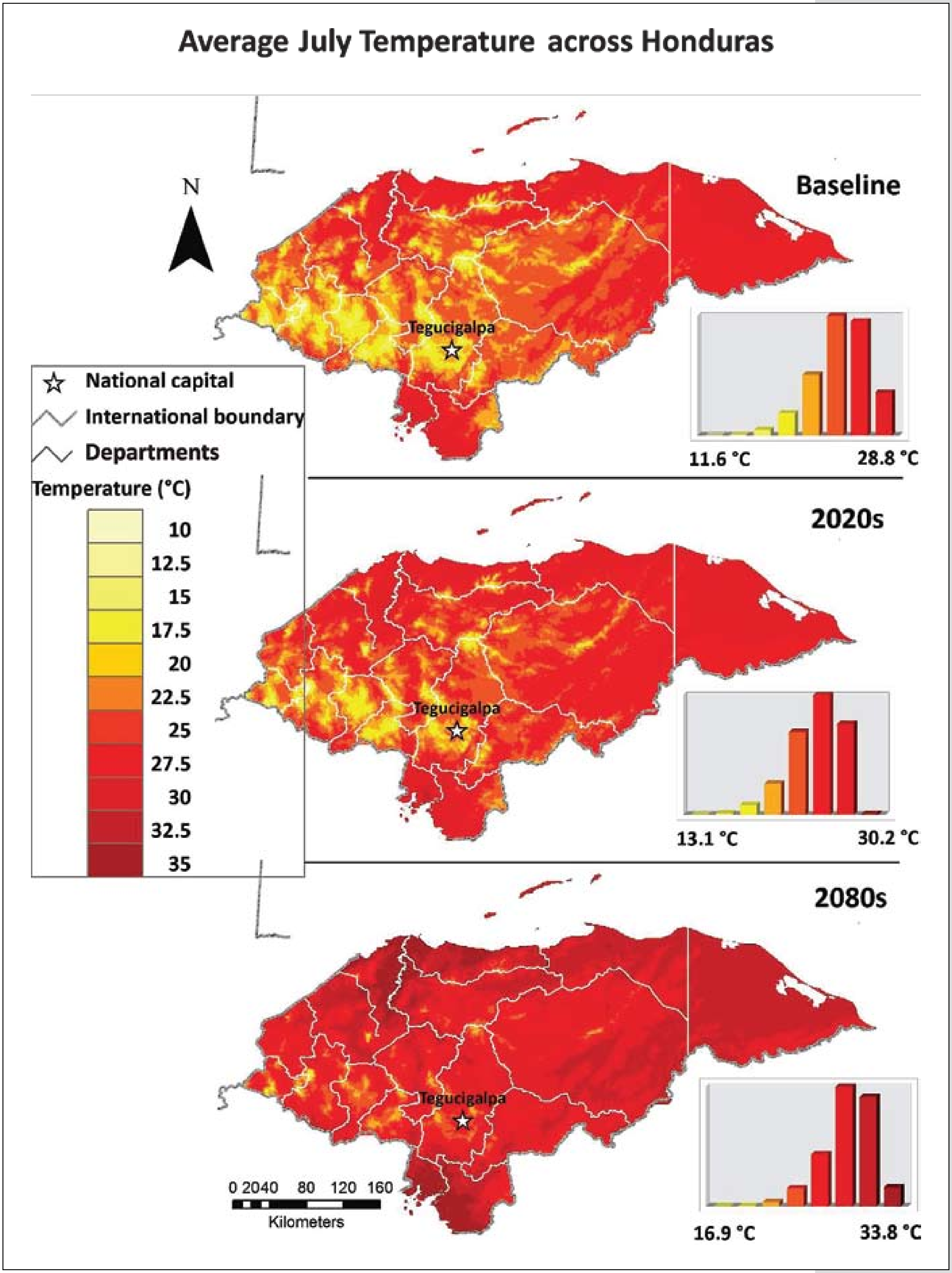


Climate Change Severity Index for Guatemala (towards the 2020s)

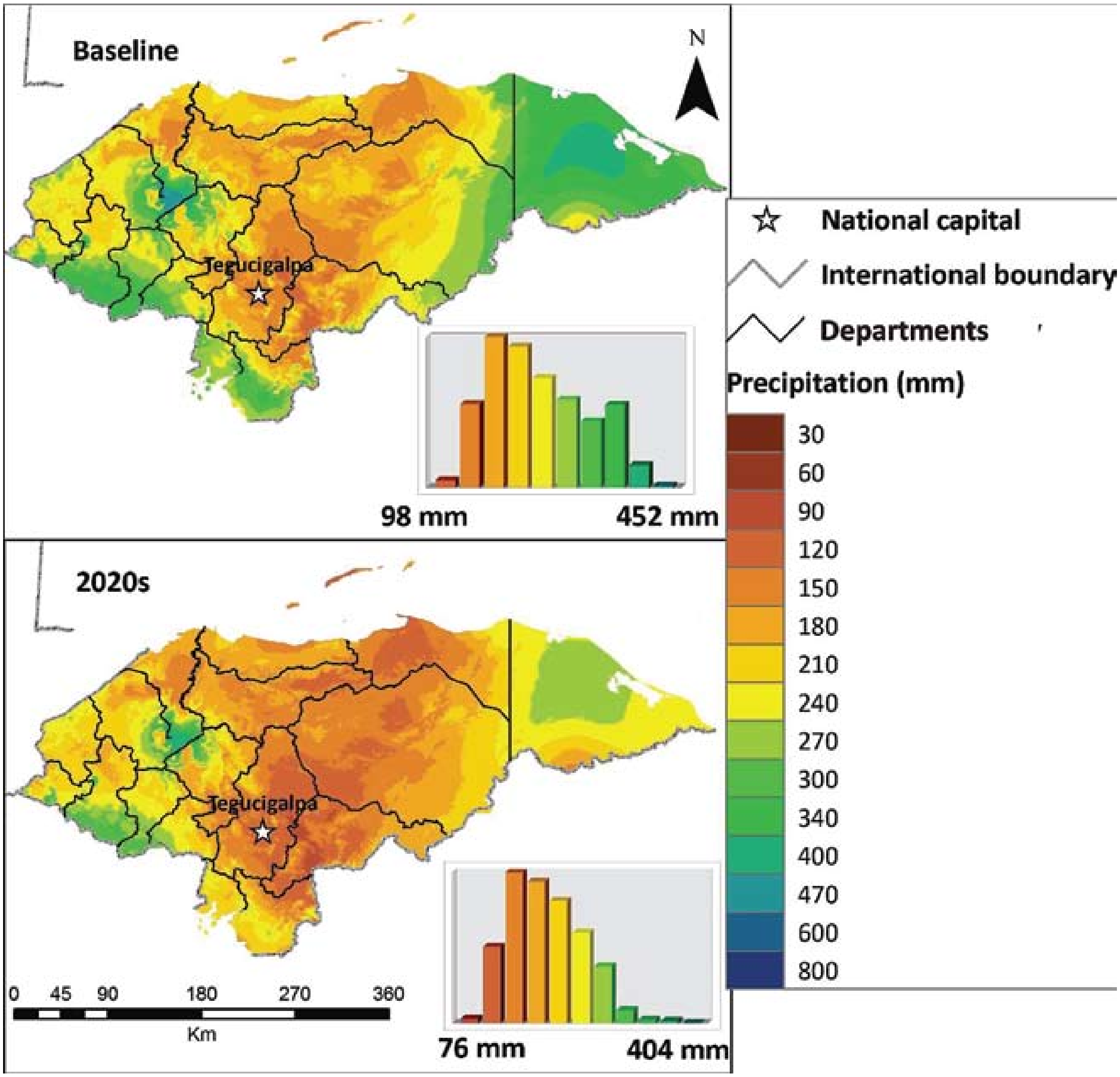


Species Richness: Honduras

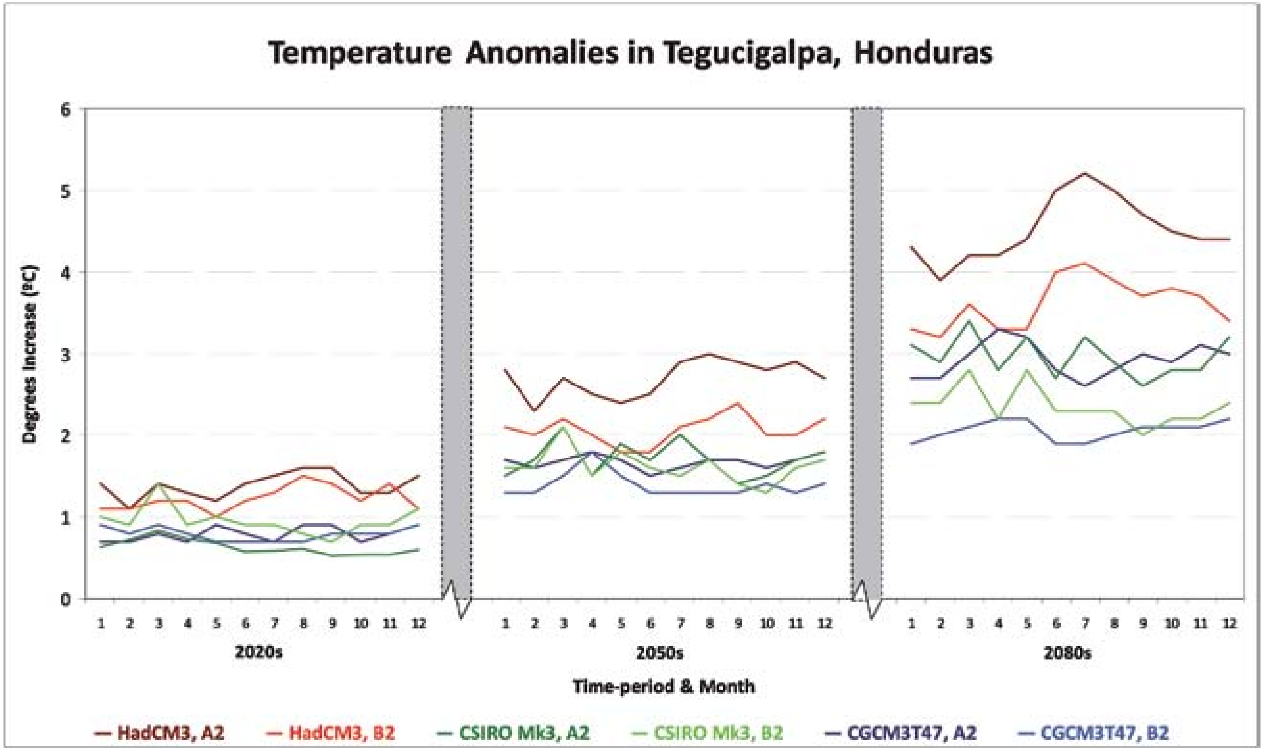


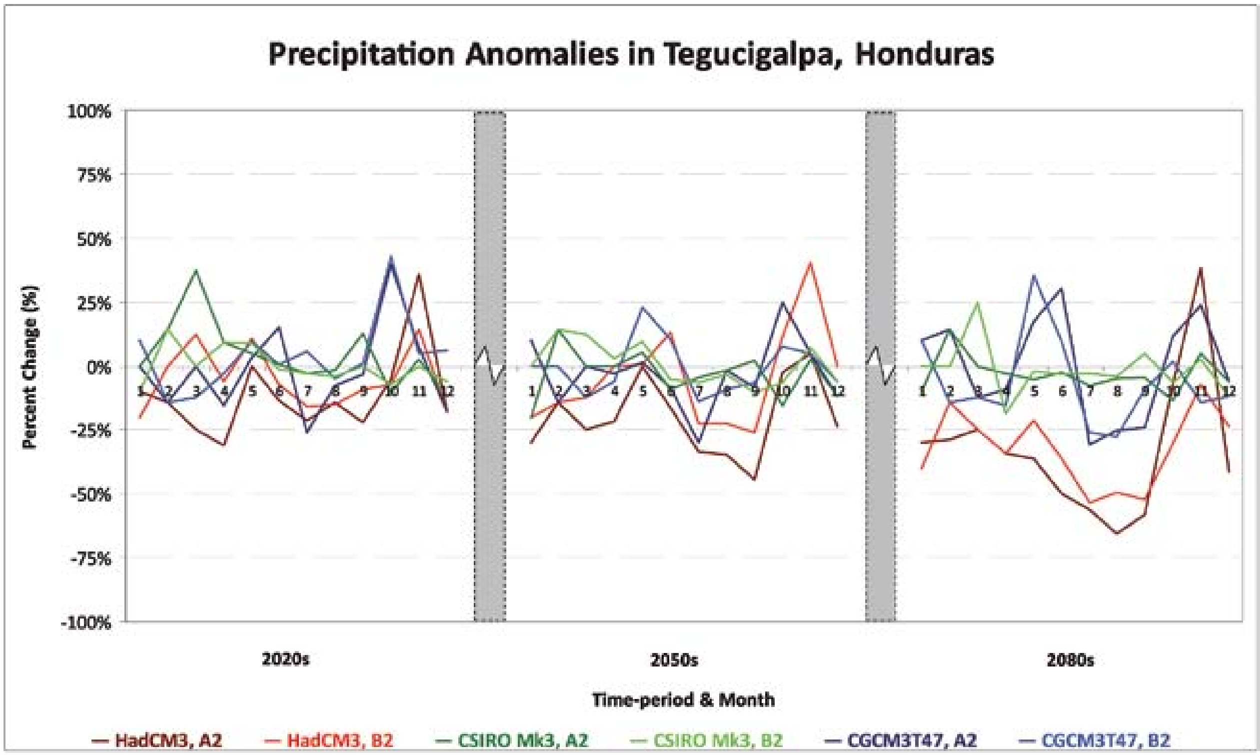

Average July Temperature across Honduras
N
Baseline
Tegucigalpa
11.6 °C
28.8 °C
2020s
Tegucigalpa
13.1 °C
30.2 °C
2080s
Tegucigalpa
16.9 °C
33.8 °C
National capital
International boundary
Departments
Temperature (°C)
10
12.5
15
17.5
20
22.5
25
27.5
30
32.5
35
0 2040 80 120 160
Kilometers

July, August, September accumulated precipitation across Honduras

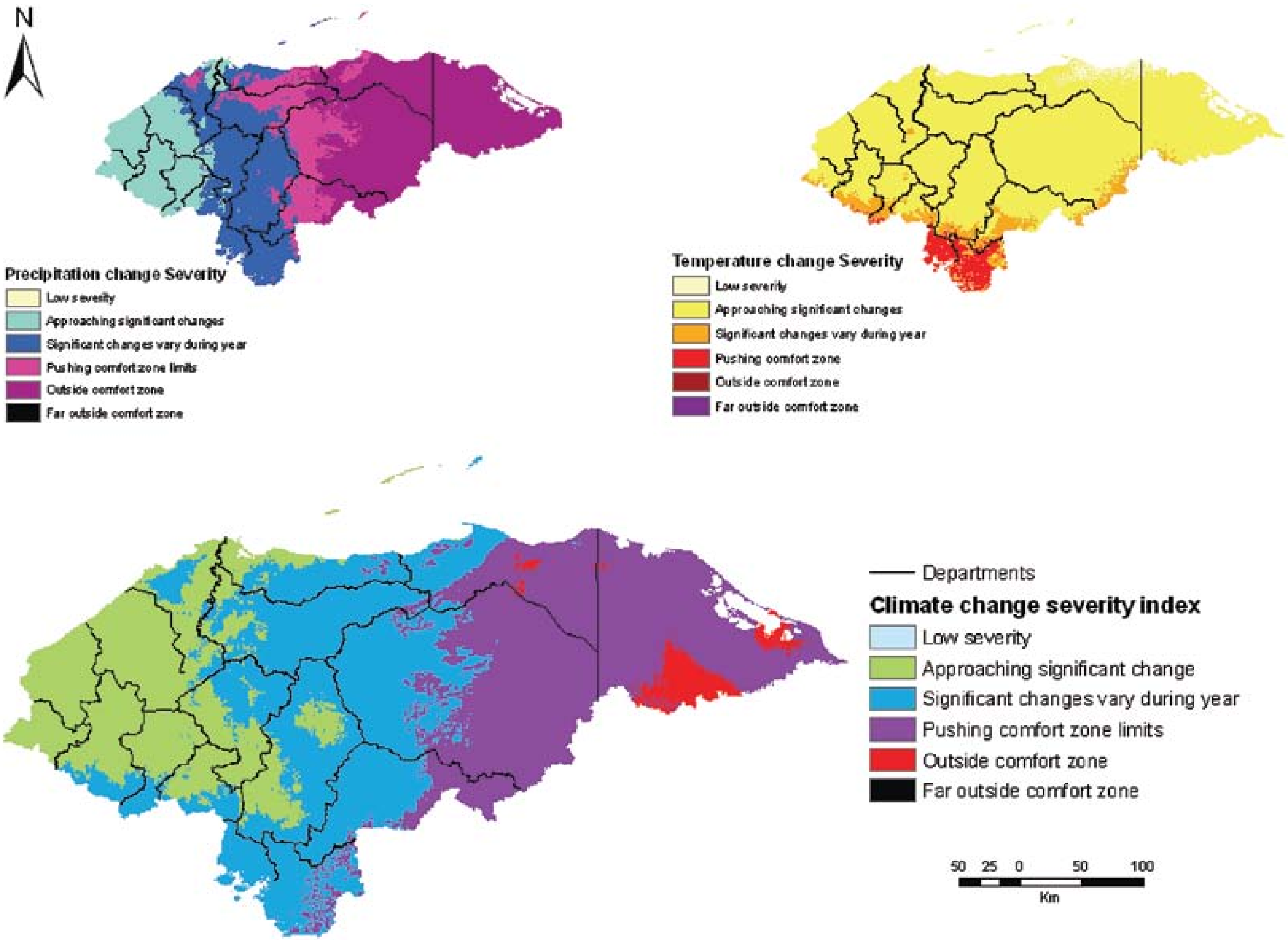


Tegucigalpa, Honduras

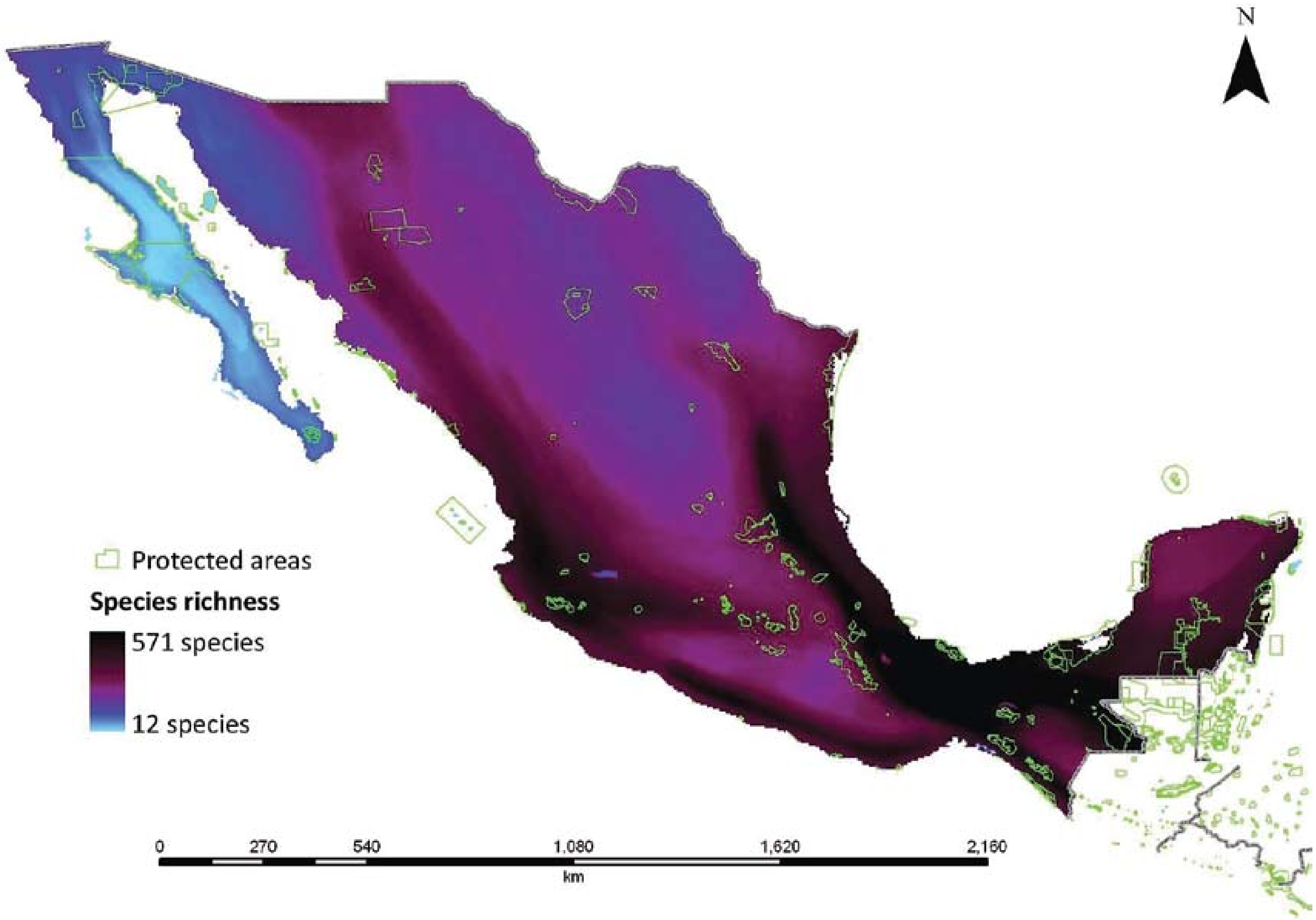


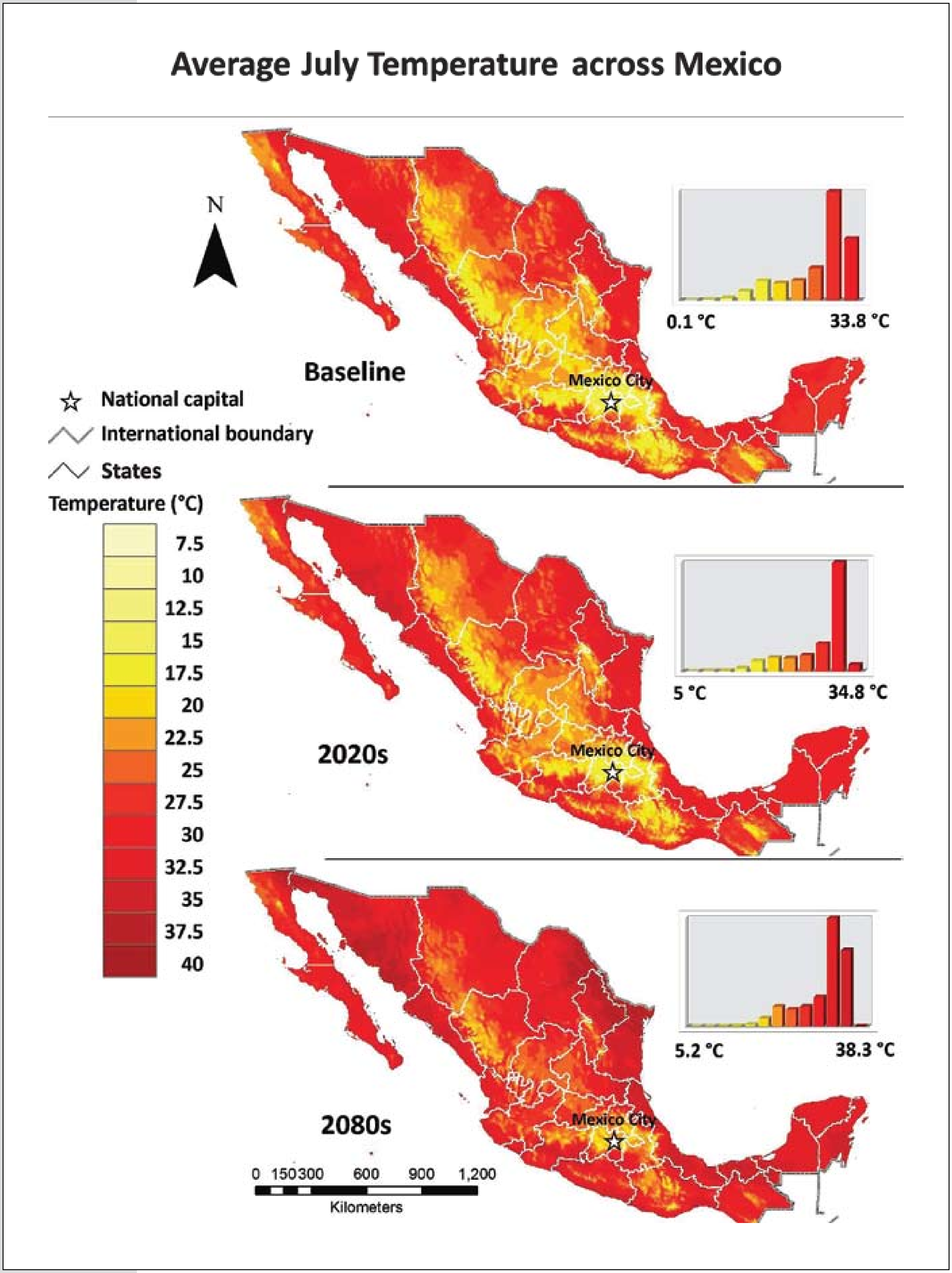


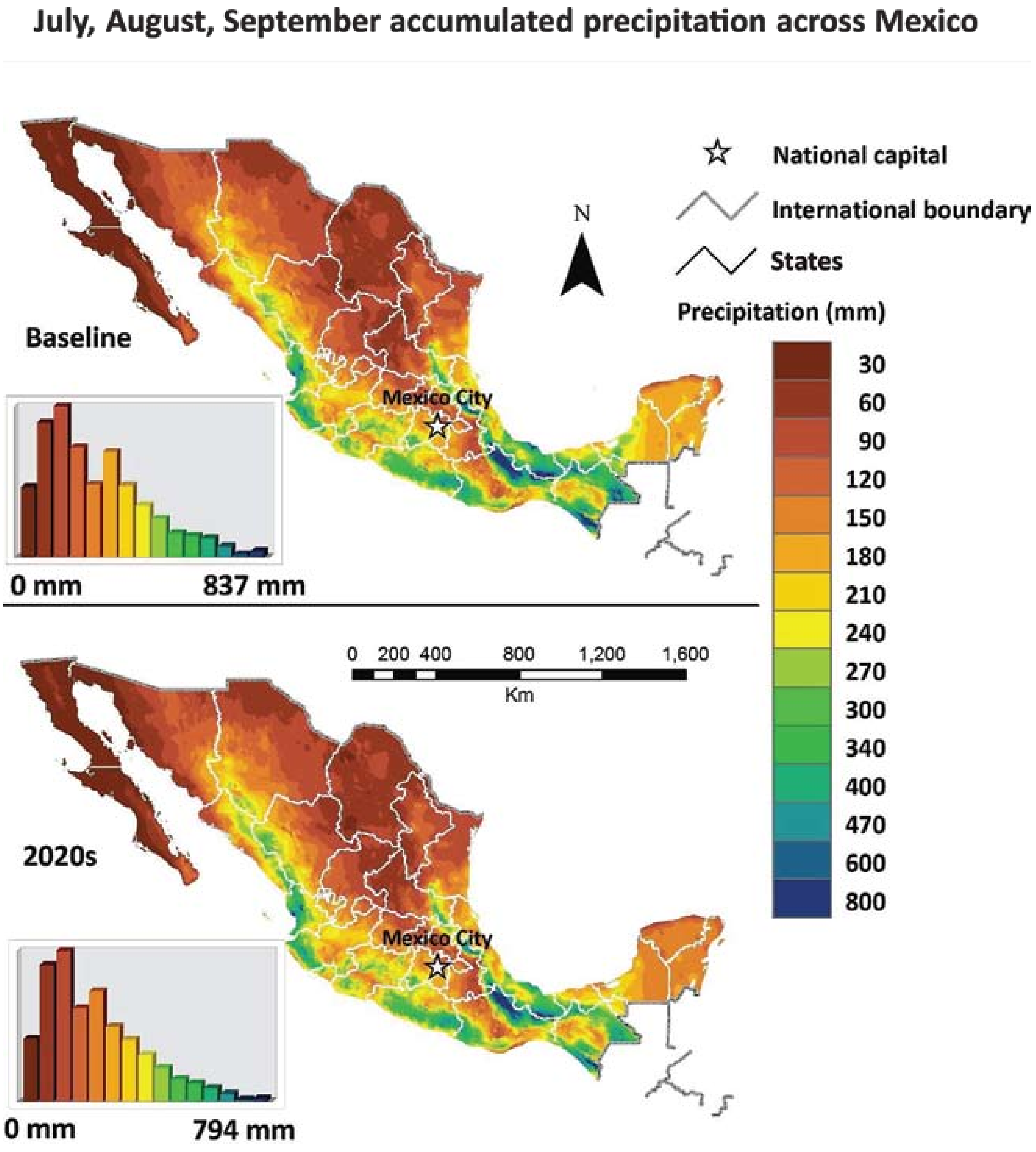
Climate Change Severity Index for Honduras (towards the 2020s)



Species Richness: Mexico

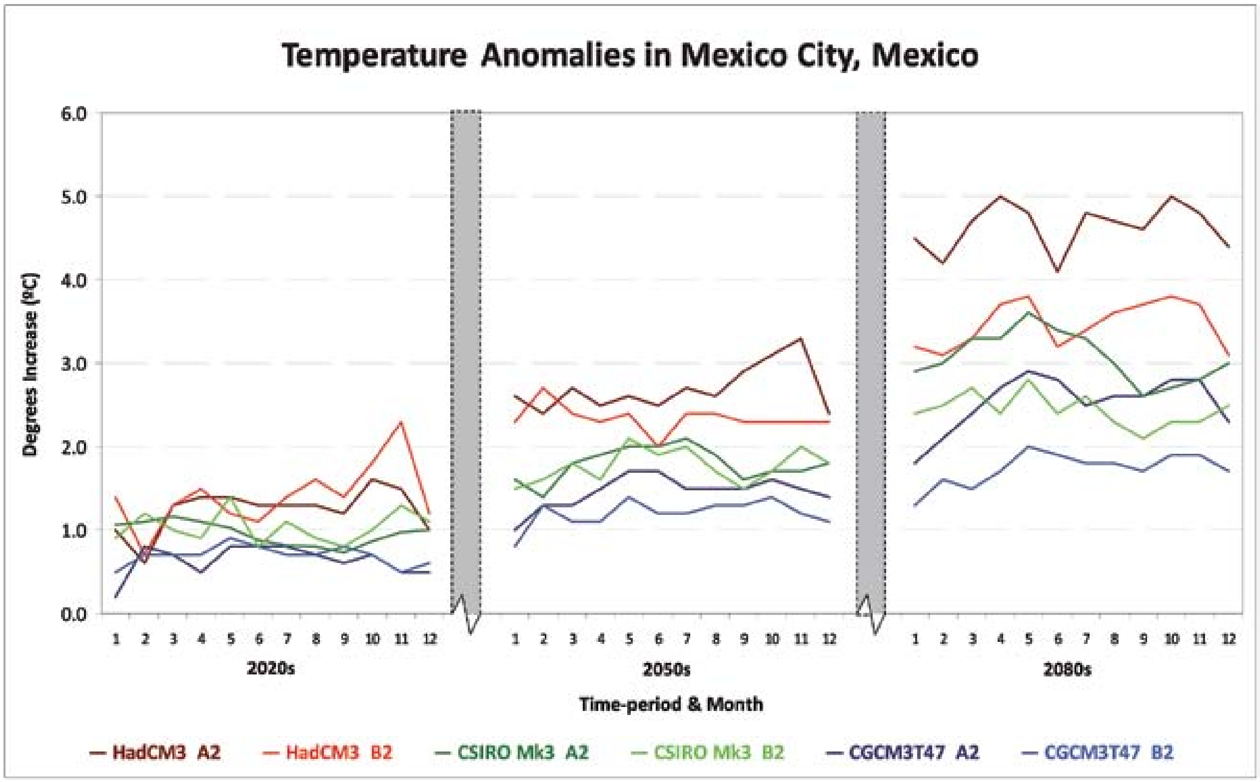


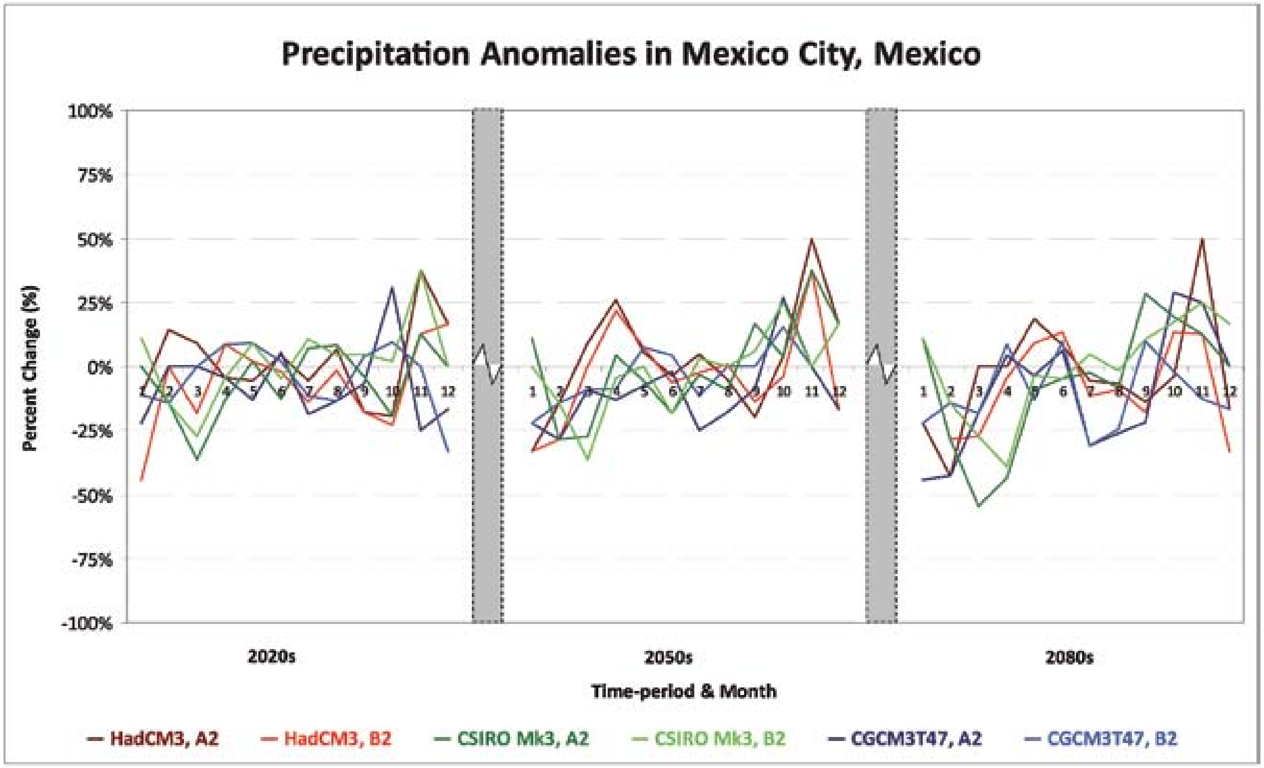

Average July Temperature across Mexico
N
Baseline
Mexico City
0.1 °C
33.8 °C
National capital
International boundary
States
Temperature (°C)
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30
32.5
35
37.5
40
2020s
Mexico City
5 °C
34.8 °C
2080s
Mexico City
5.2 °C
38.3 °C
0 150300 600 900 1,200
Kilometers



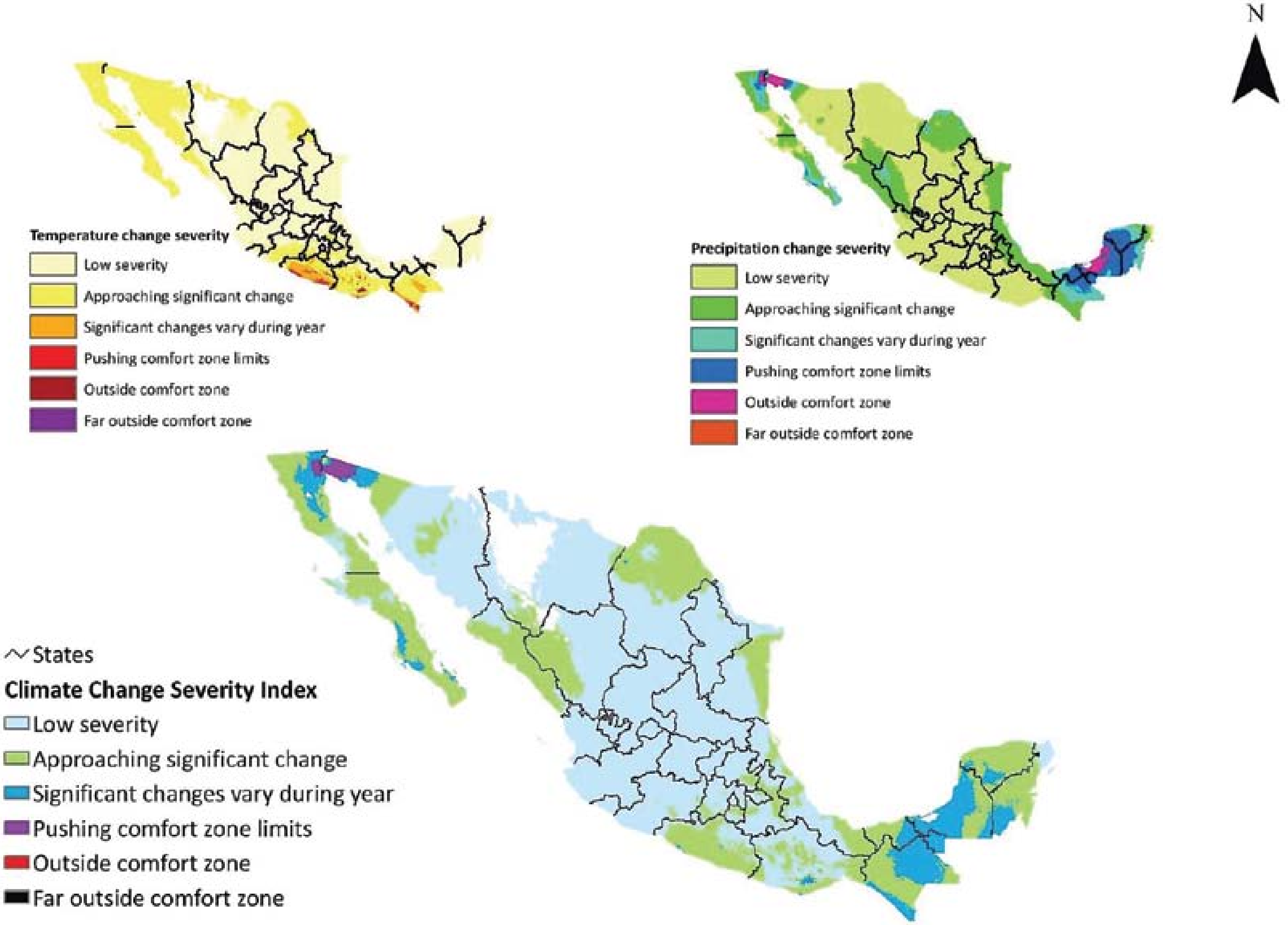
July, August, September accumulated precipitation across Mexico

Mexico City, Mexico

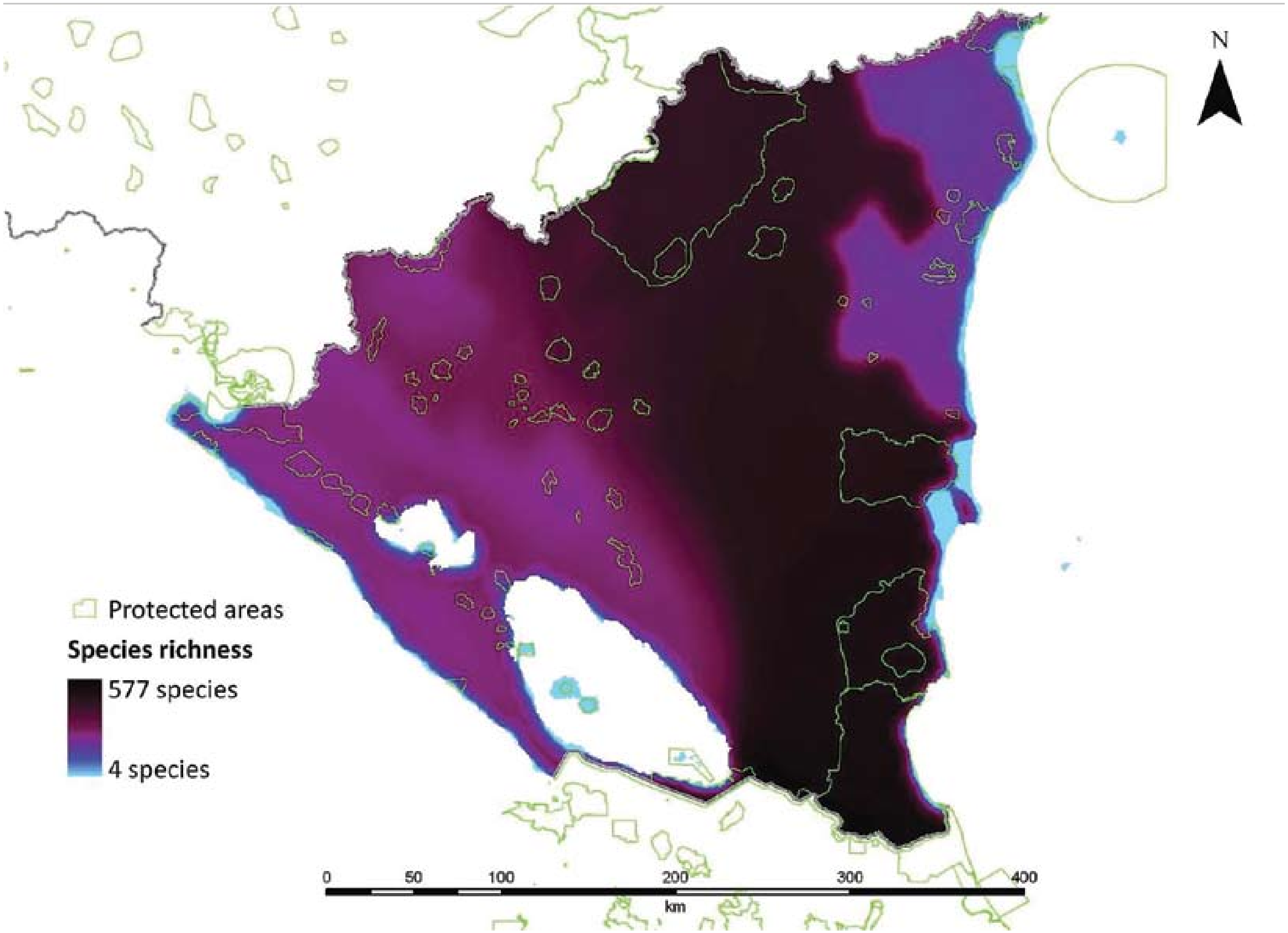


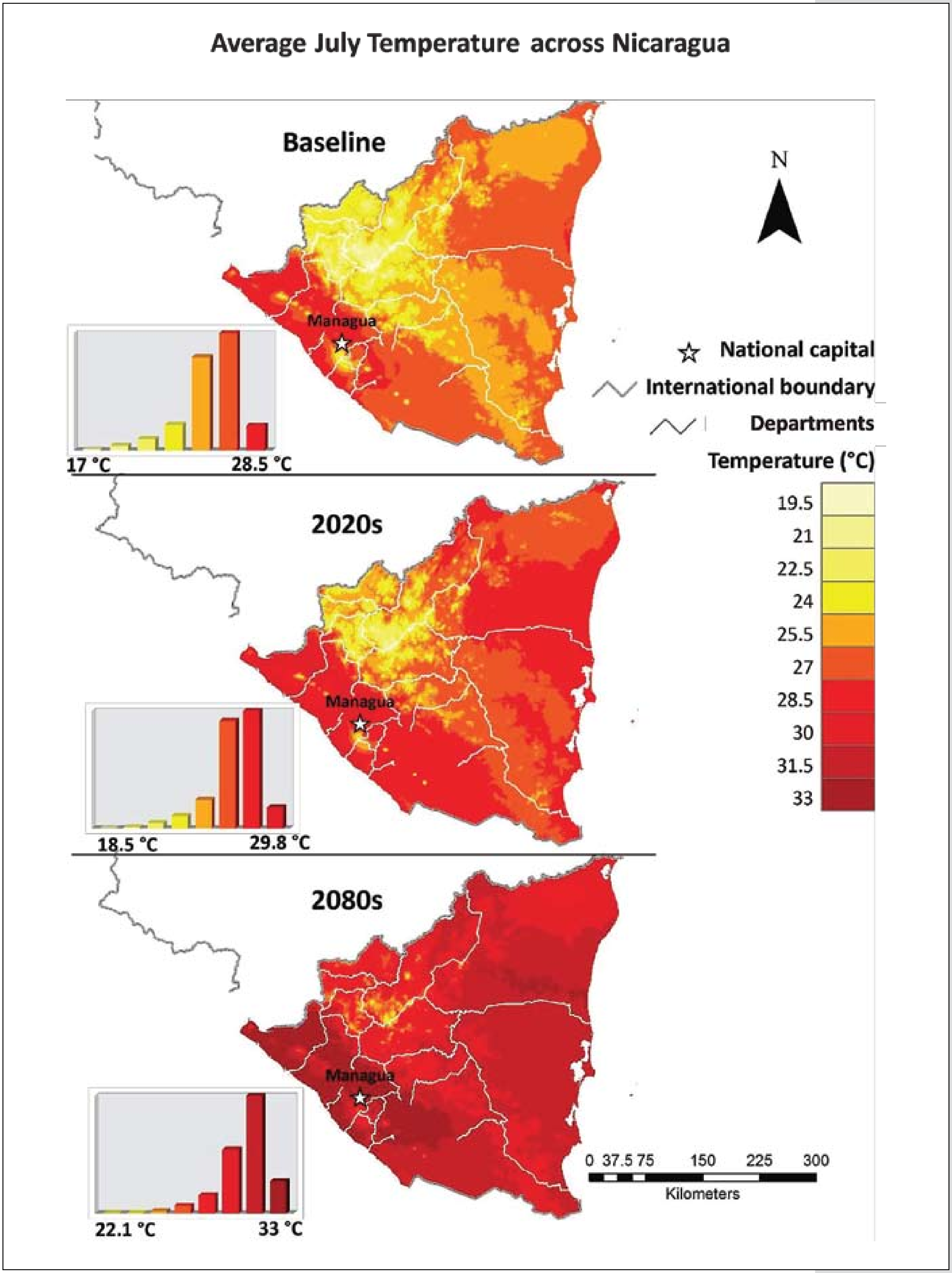


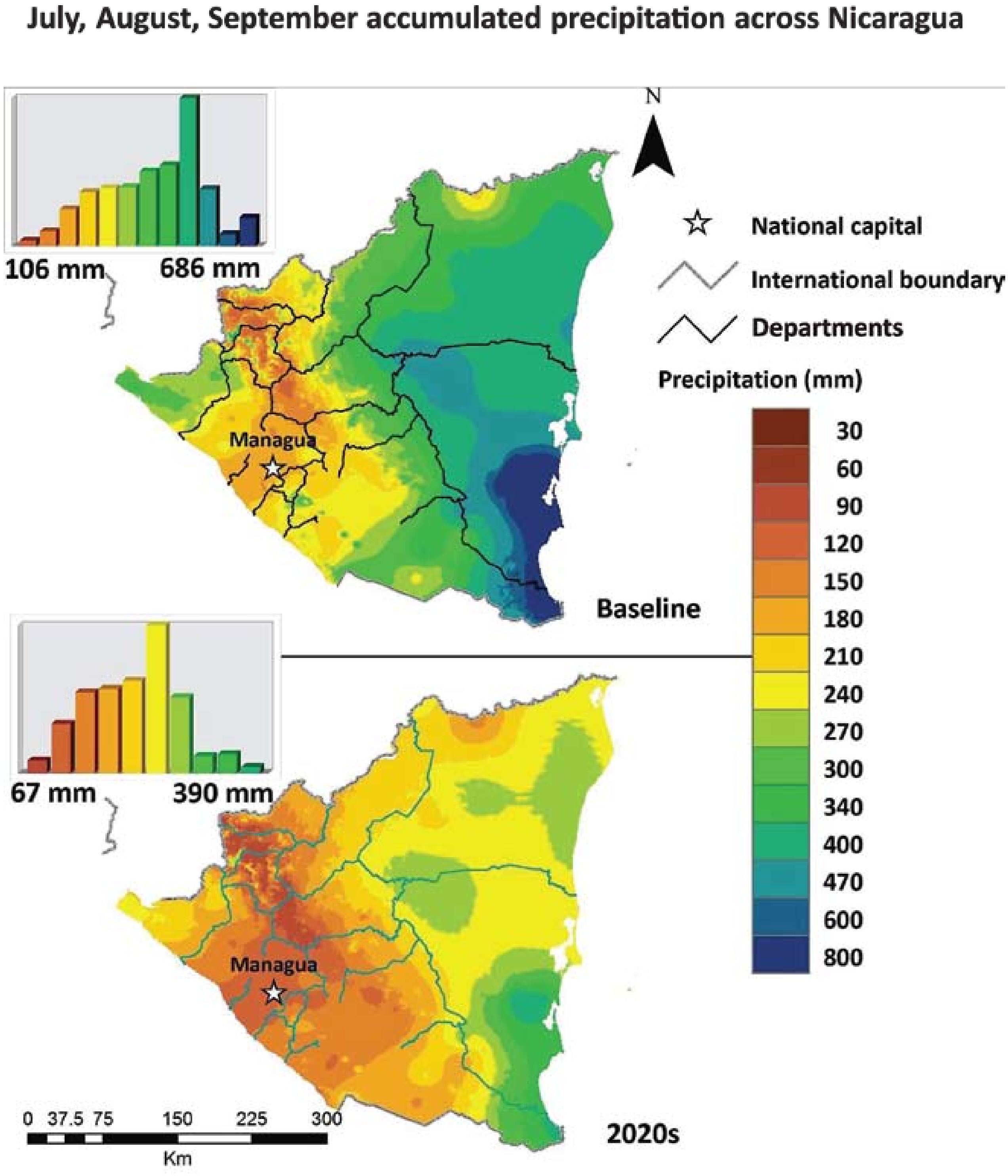
Climate Change Severity Index for Mexico (towards the 2020s)



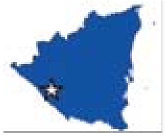
Species Richness: Nicaragua



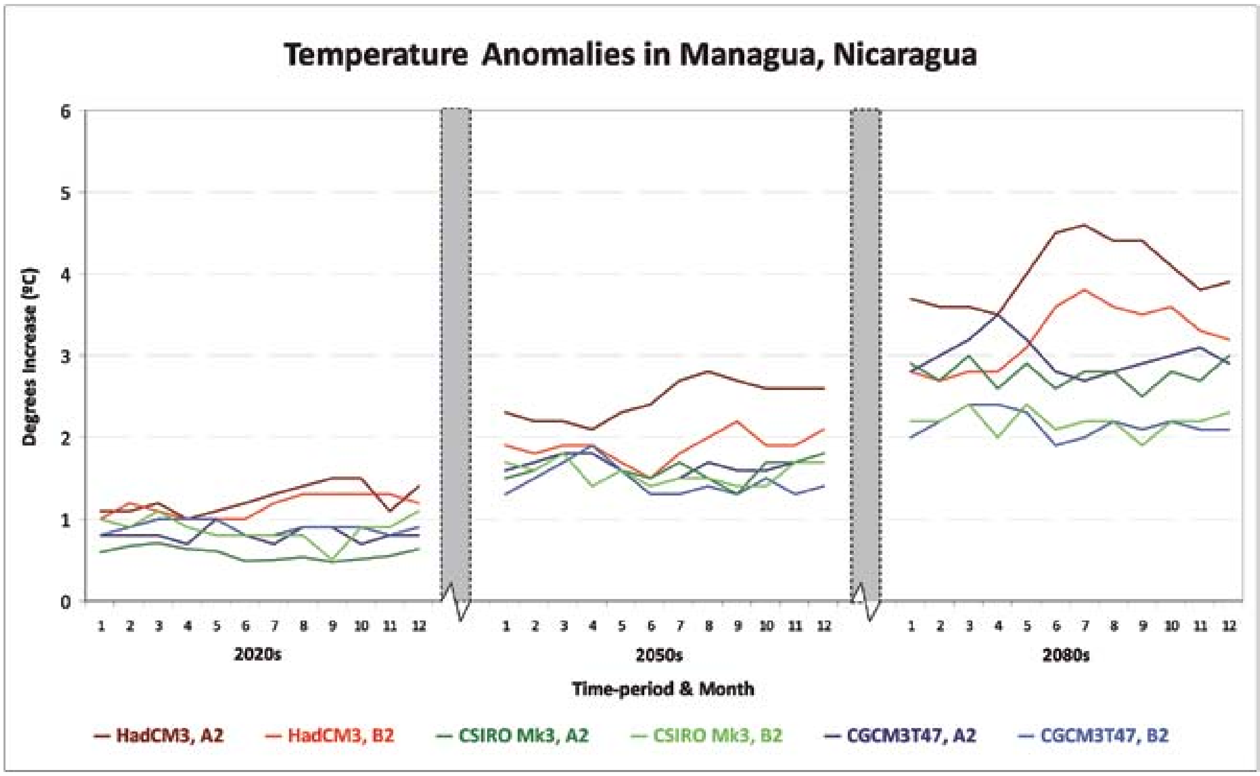

Average July Temperature across Nicaragua
Baseline
Managua
17 °C
28.5 °C
2020s
Managua
18.5 °C
29.8 °C
2080s
Managua
22.1 °C
33 °C
N
National capital
International boundary
Departments
Temperature (°C)
19.5
21
22.5
24
25.5
27
28.5
30
31.5
33
0 37.5 75 150 225 300
Kilometers

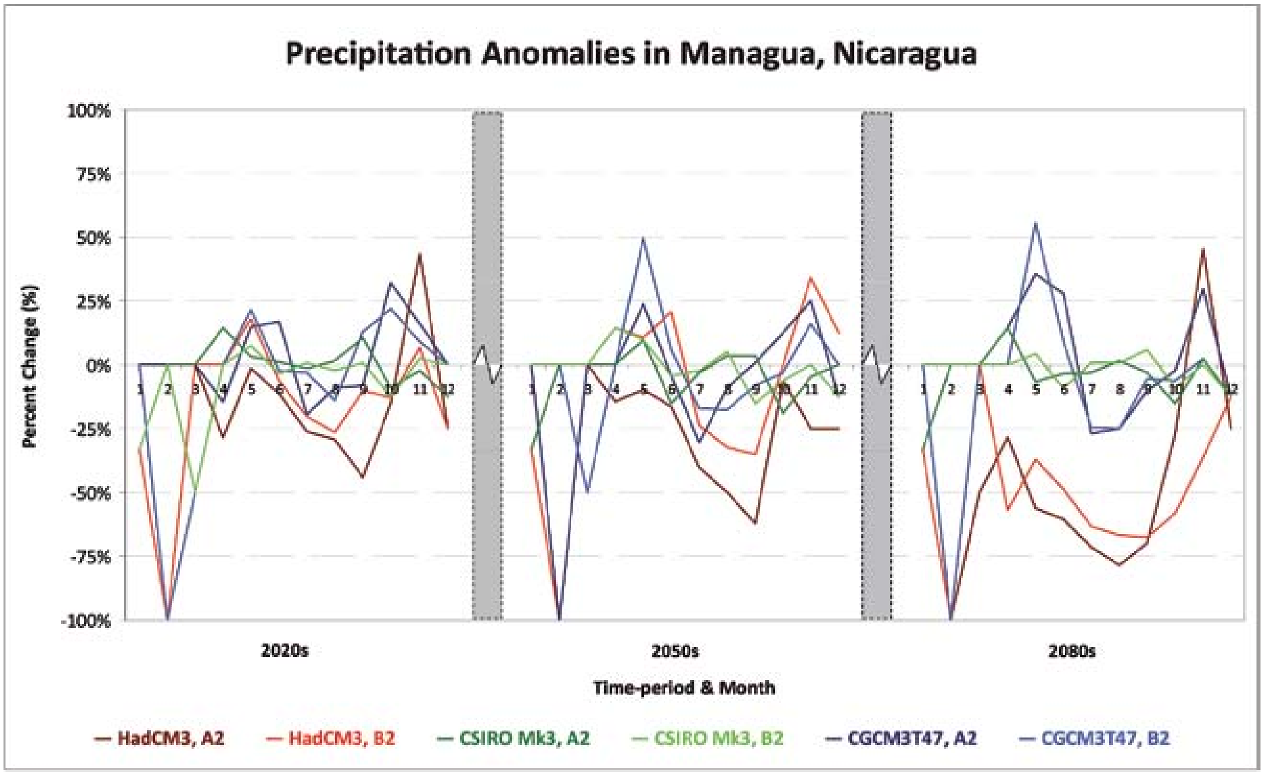


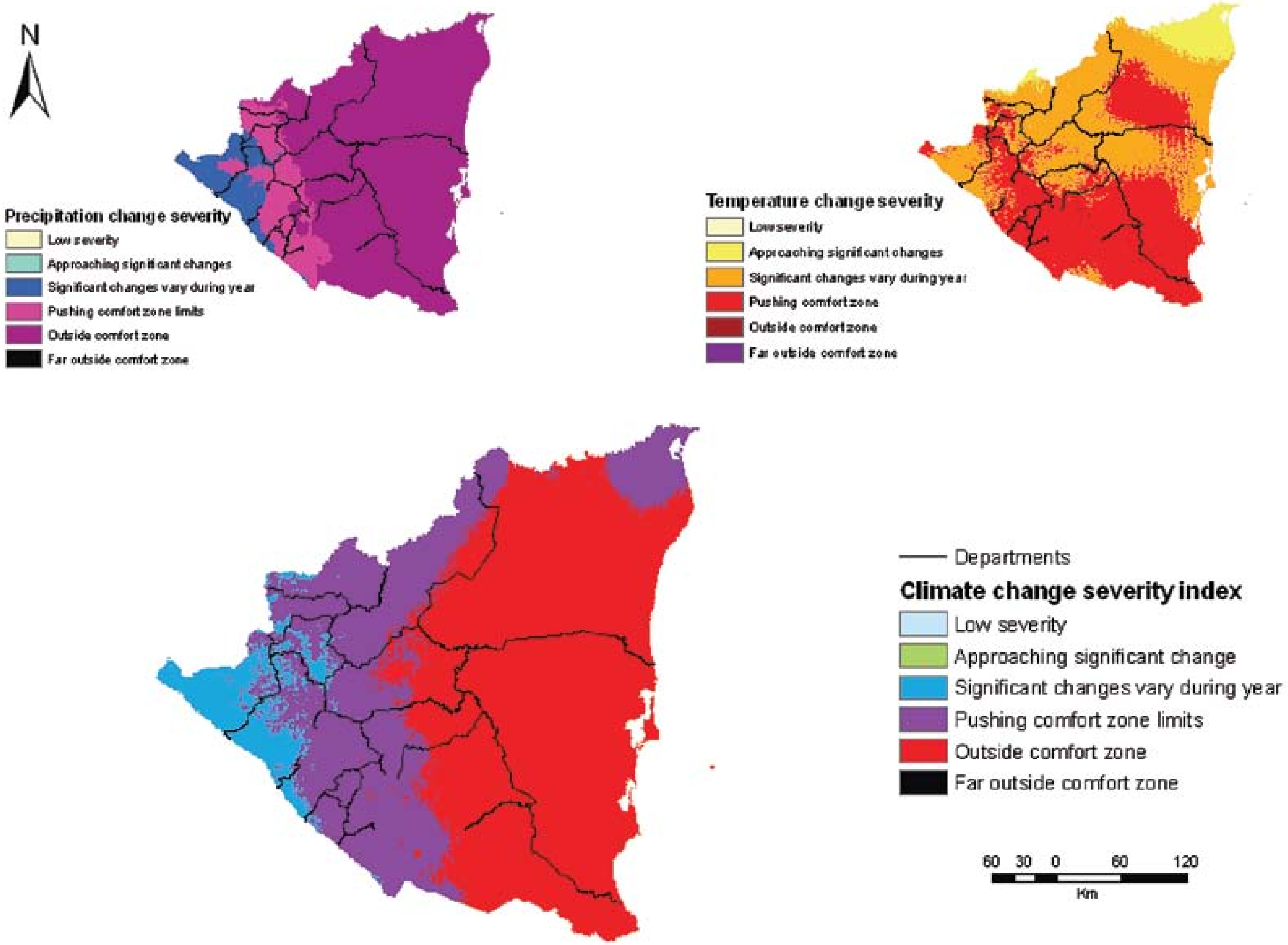
July, August, September accumulated precipitation across Nicaragua



Managua, Nicaragua

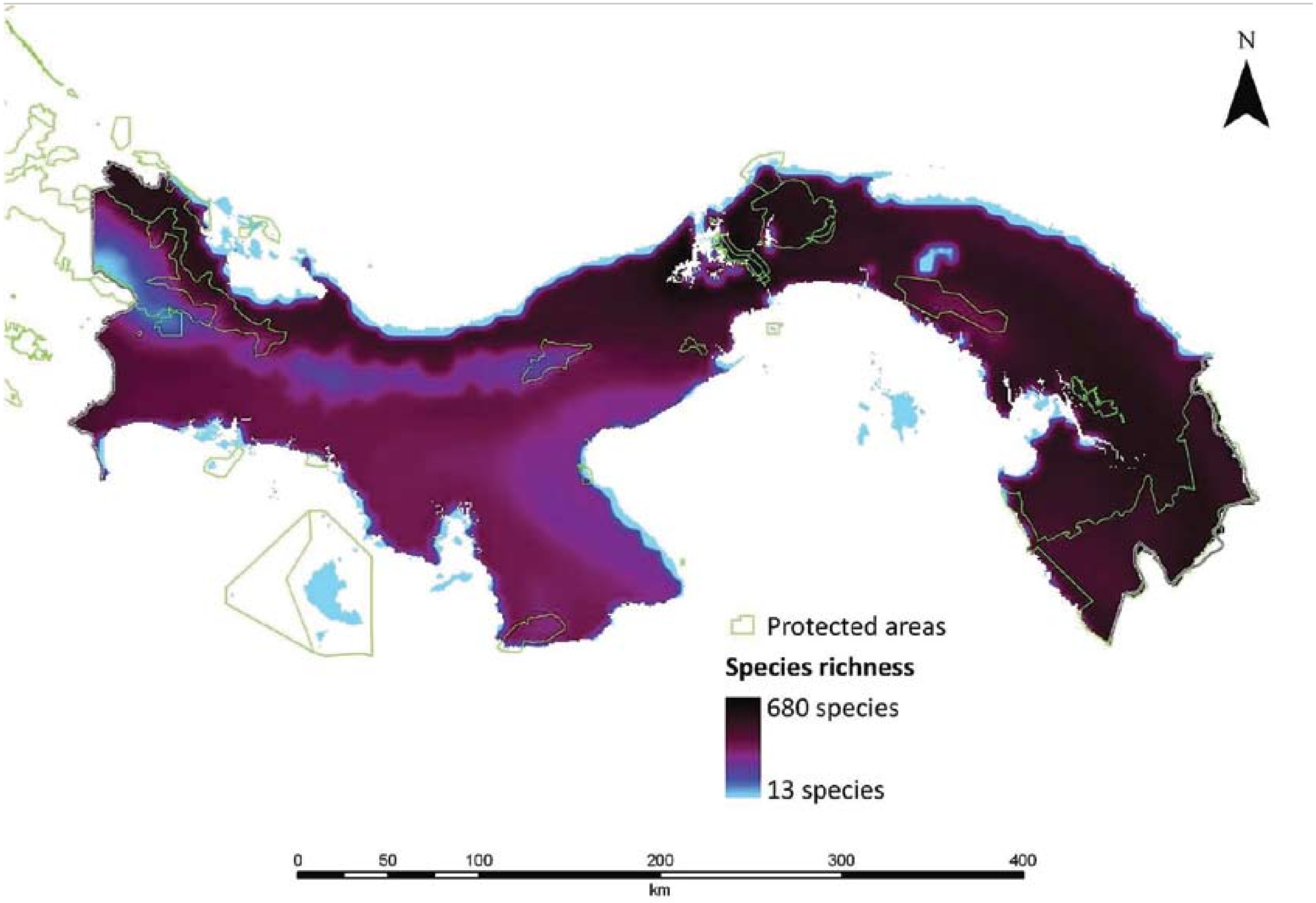


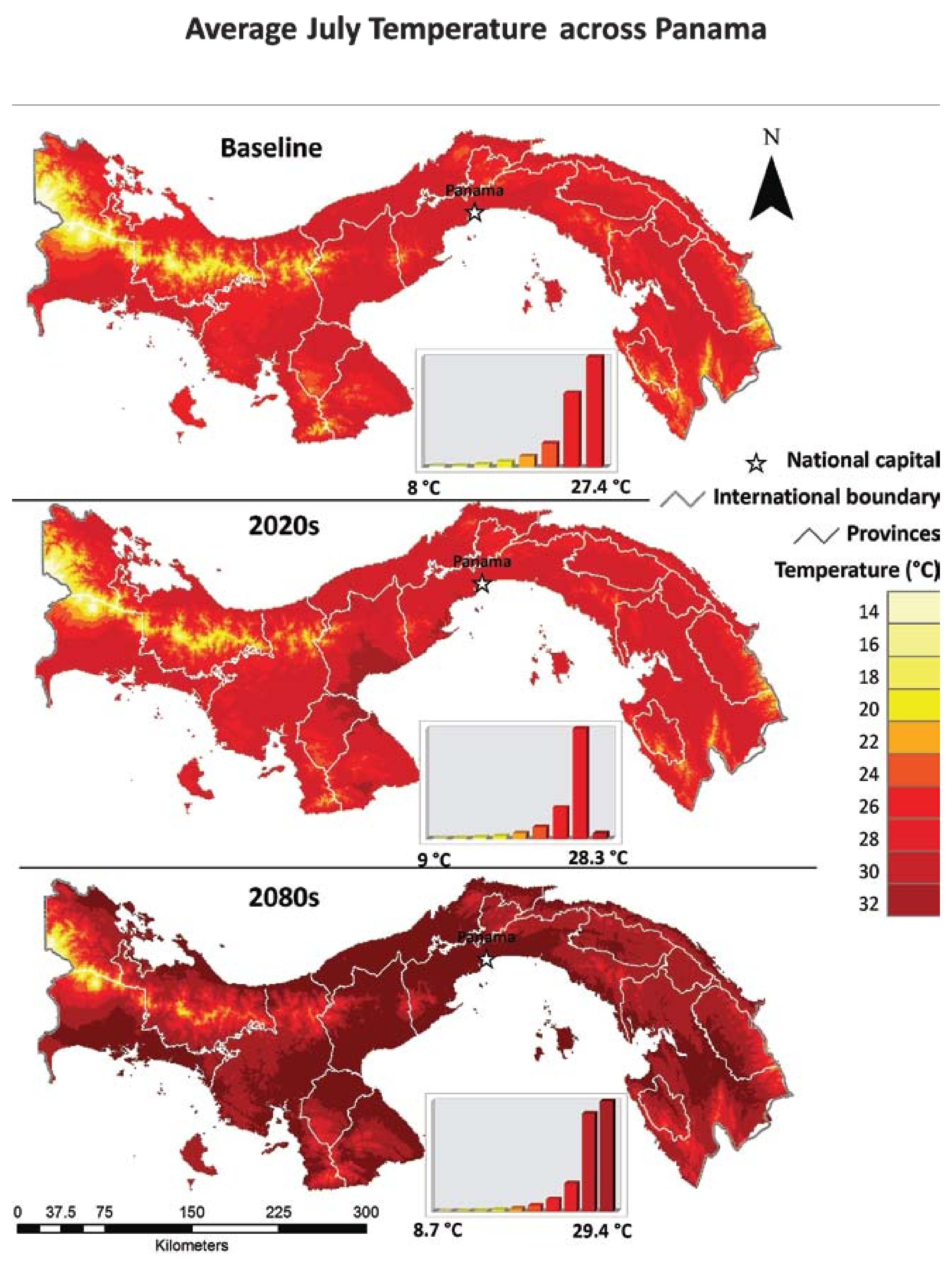




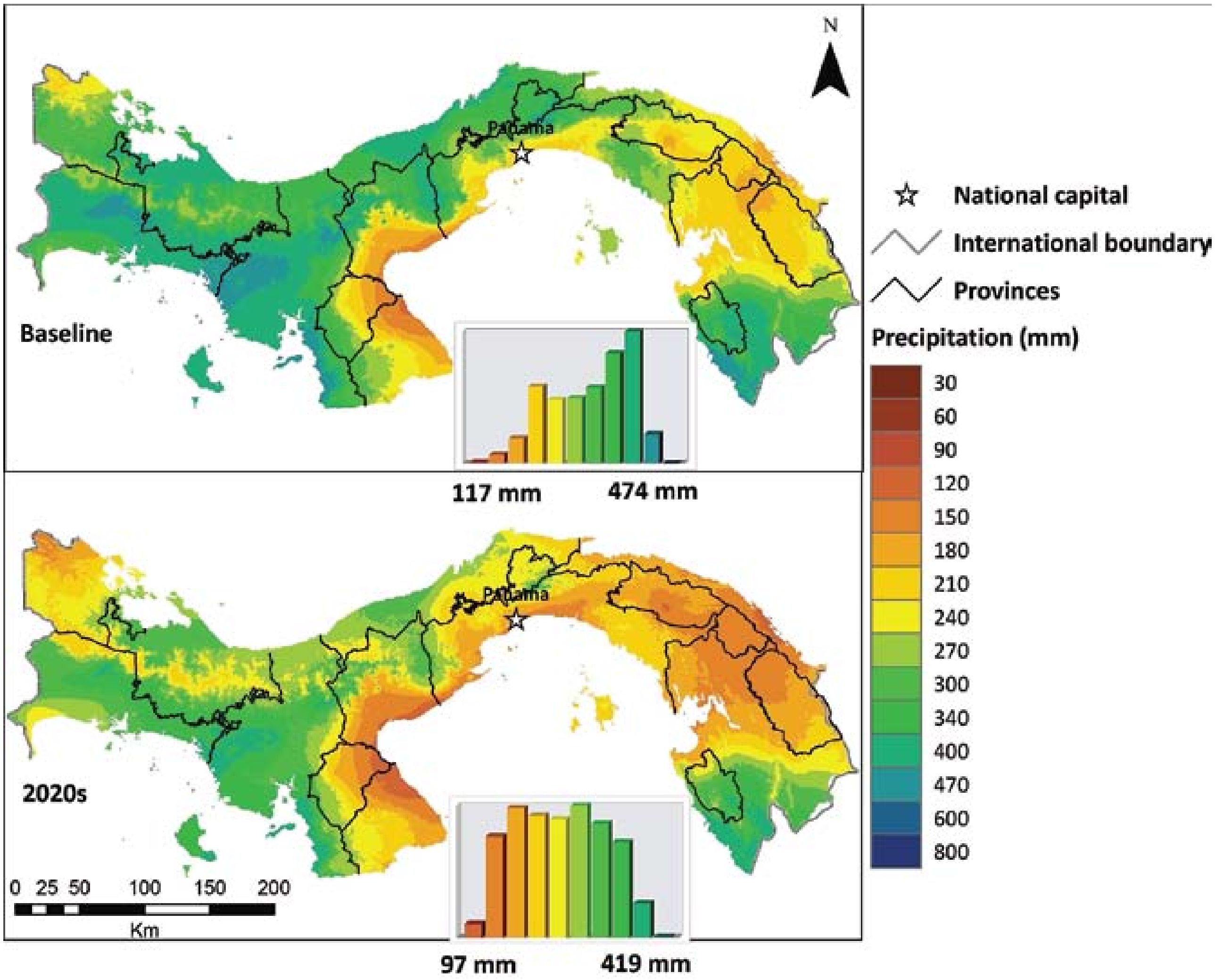
Climate Change Severity Index for Nicaragua (towards the 2020s)

Species Richness: Panama

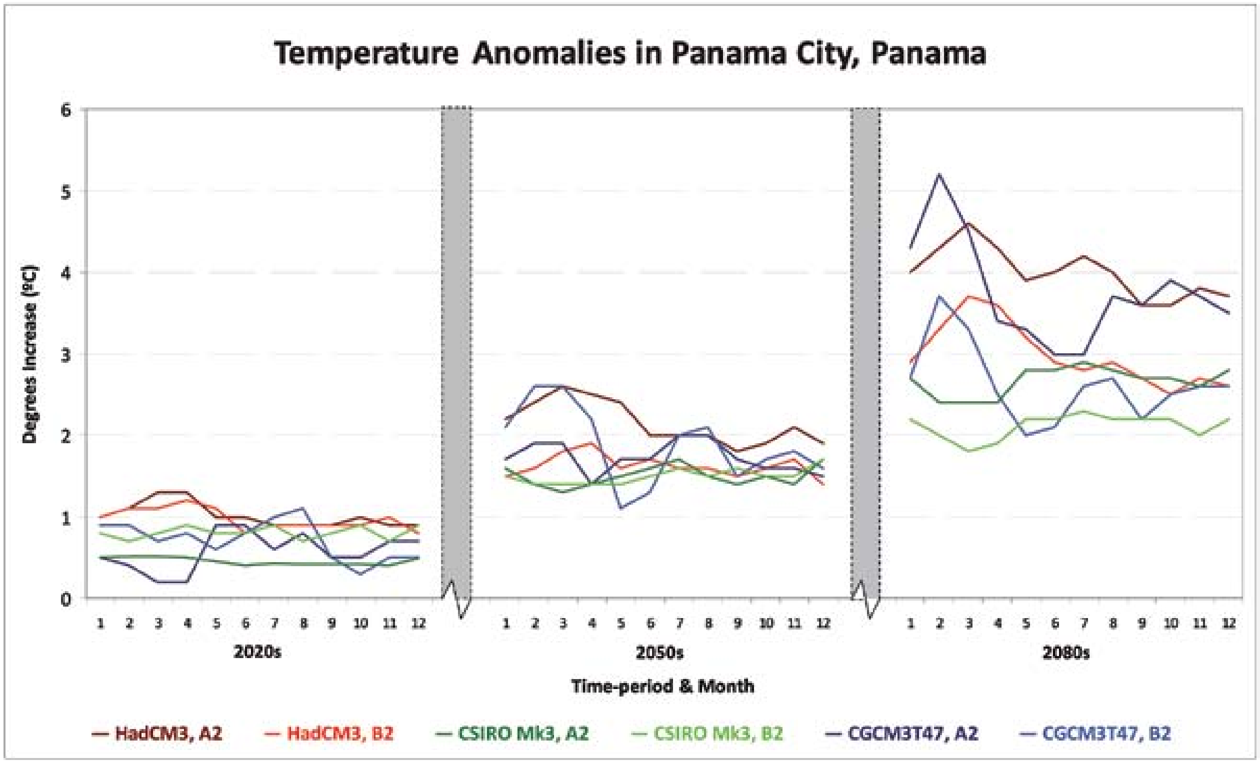


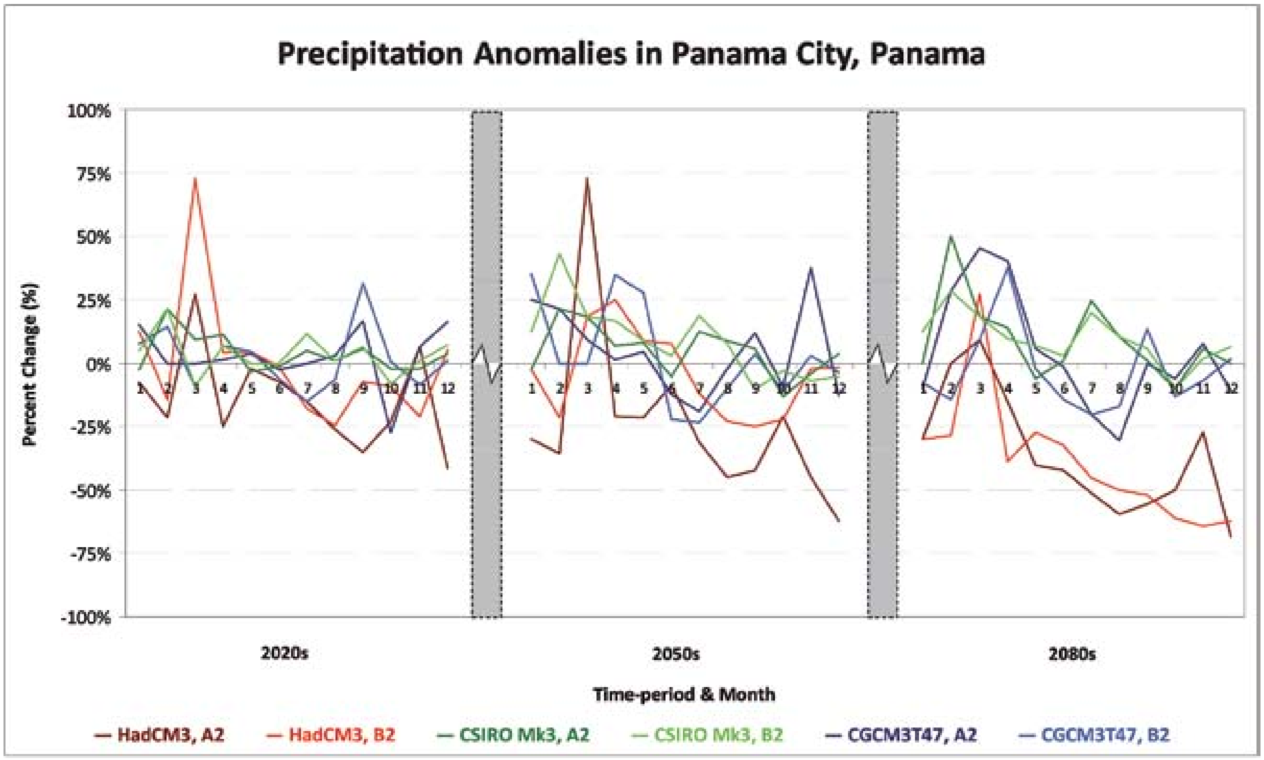

Average July Temperature across Panama
Baseline
N
Panama
8 °C
27.4 °C
2020s
Panama
9 °C
28.3 °C
2080s
Panama
8.7 °C
29.4 °C
National capital
International boundary
Provinces
Temperature (°C)
14
16
18
20
22
24
26
28
30
32
0
37.5
75
150
225
300
Kilometers

July, August, September accumulated precipitation across Panama

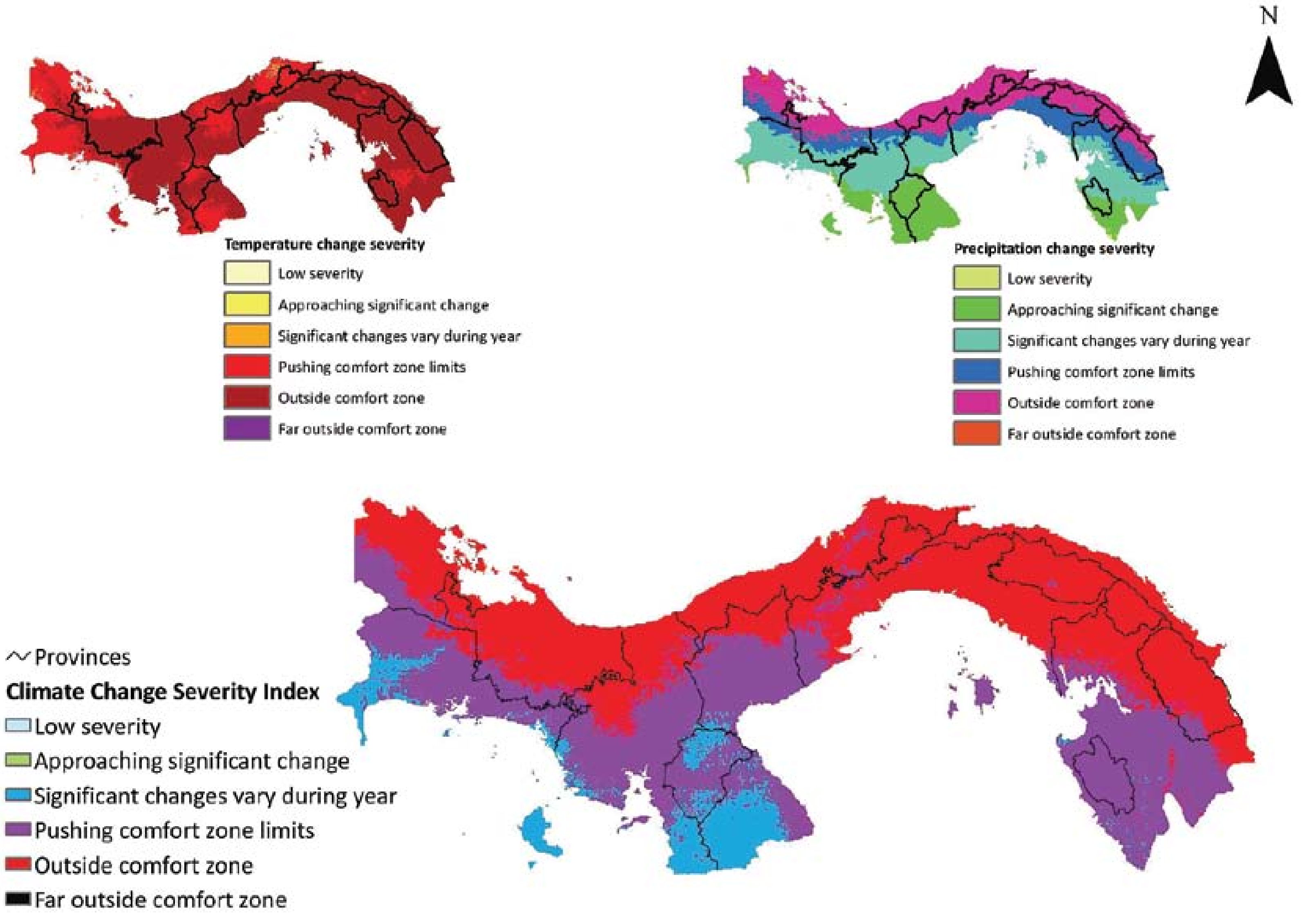


Panama City, Panama


Temperature Anomalies in Panama City, Panama


Precipitation Anomalies in Panama City, Panama

Climate Change Severity Index for Panama (towards the 2020s)



APPENDIX B: CLIMATE CHANGE SEVERITY IN ECOSYSTEMS

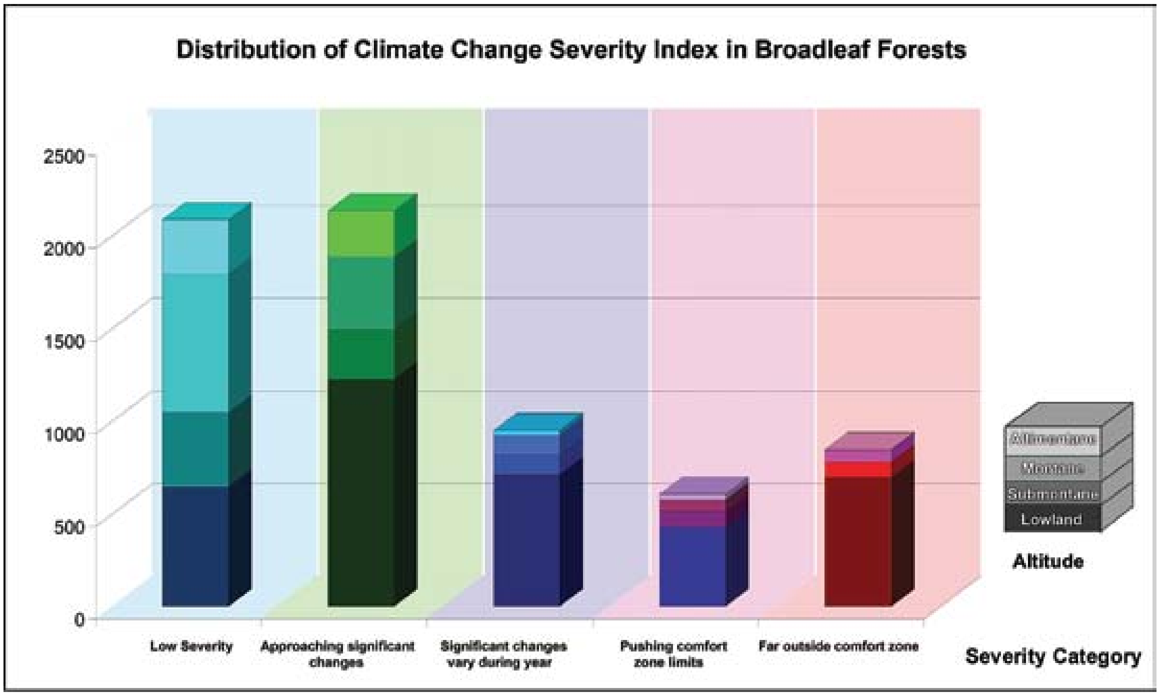
This appendix provides average CCSI values for each ecosystem as delineated specifically for this study. As shown earlier in this report, we included in the ecosystem classification major vegetation or land cover type and altitude. Broadleaf forest, coniferous forest, mixed forest, savanna, and shrubland, have been separated into four distinct classifications based on elevation. We divide elevation into lowland, submontane, montane, and altimontane, where the actual values depend upon an ecosystem's location on the Pacific or Atlantic slope, adapting the classification scheme utilized in the Central America Ecosystems Mapping Project:

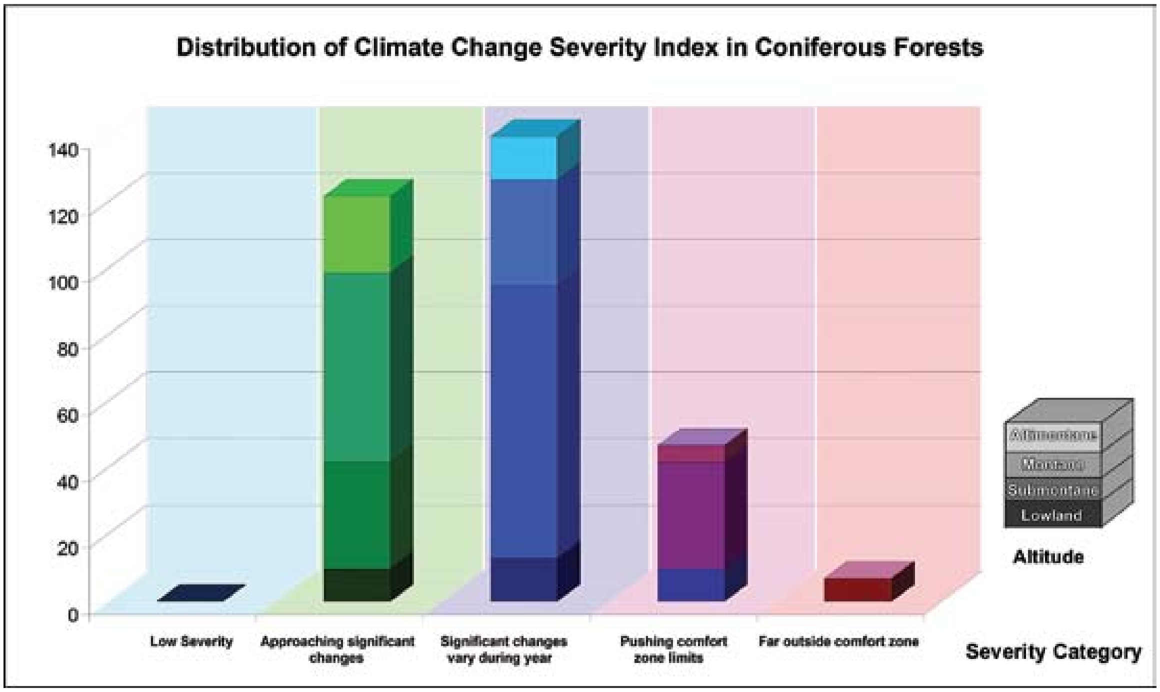
Altitudinal descriptors	Elevation (meters)	
	Atlantic slope	Pacific slope
Lowland	0 – 500	0 – 700
Submontane	500 – 1,000	700 – 1,200
Montane	1,000 – 2,000	1,200 – 2,300
Altimontane	> 2000	> 2,300

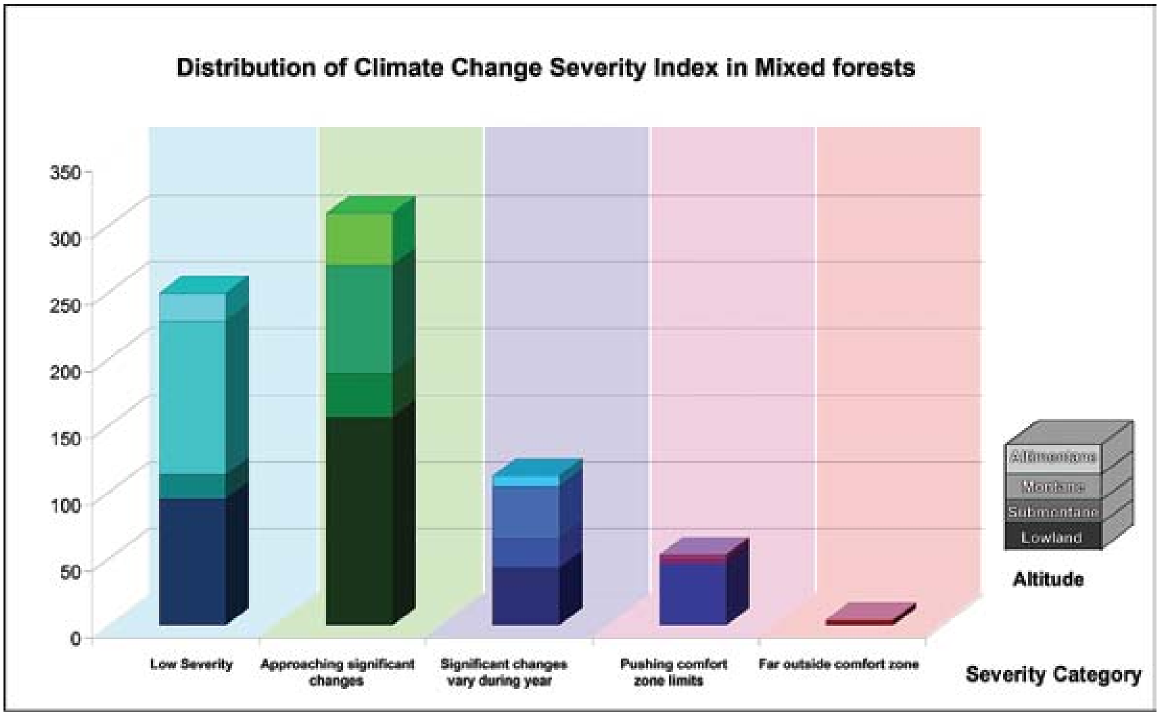
Additionally, we include mangroves, wetlands, agriculture, and urban areas, but we have not divided them up into altitudinal classes. However, since the main objective in developing the CCSI is to better describe the severity of potential impacts on species and natural ecosytems, we do not include summarized CCSI values for urban areas.

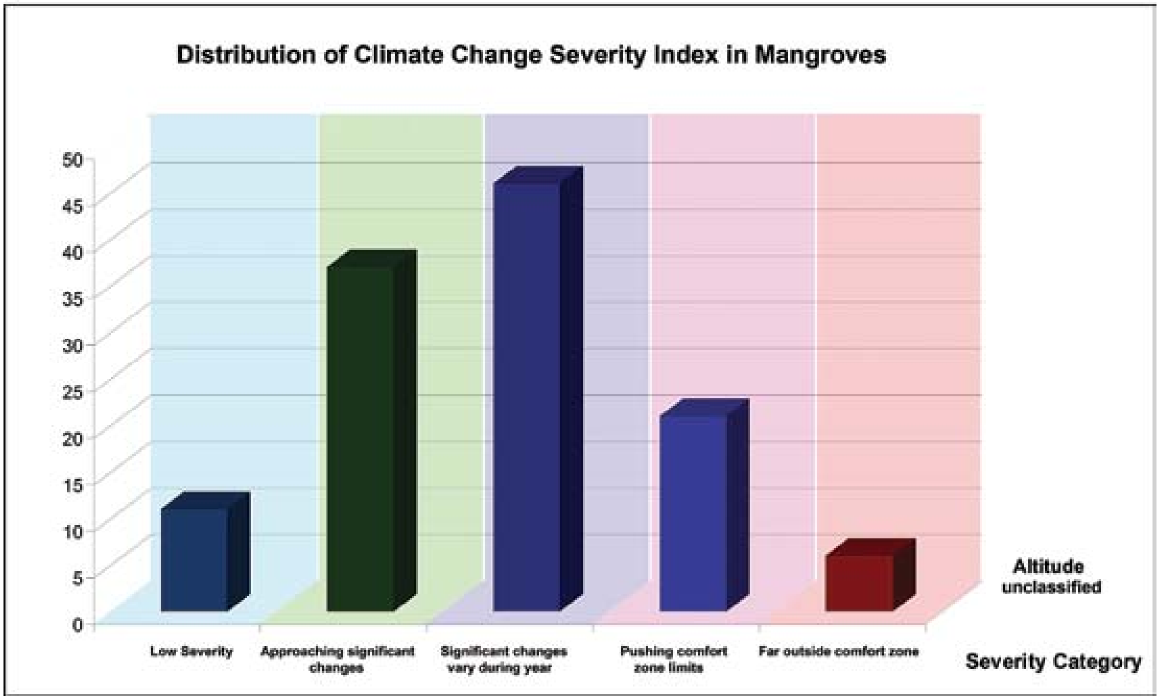
Equal amounts of land have not been assigned to each ecosystem type, so some ecosystem classes are very large, while others are small. The units in the histograms are very roughly in 100 km². This should serve as an approximate reference in order to understand the varying extents of each ecosystem and altitudinal class. One should also consider that these histograms represent average CCSI values derived from Worldclim's downscaling of the Hadley Couple Climate Model, version 3, Scenario A2, meaning that the results comprise some of the "worst case scenarios." Regardless, we calculate these CCSI values using the 2020s projection, where there is a very high level of agreement among different models and scenarios.

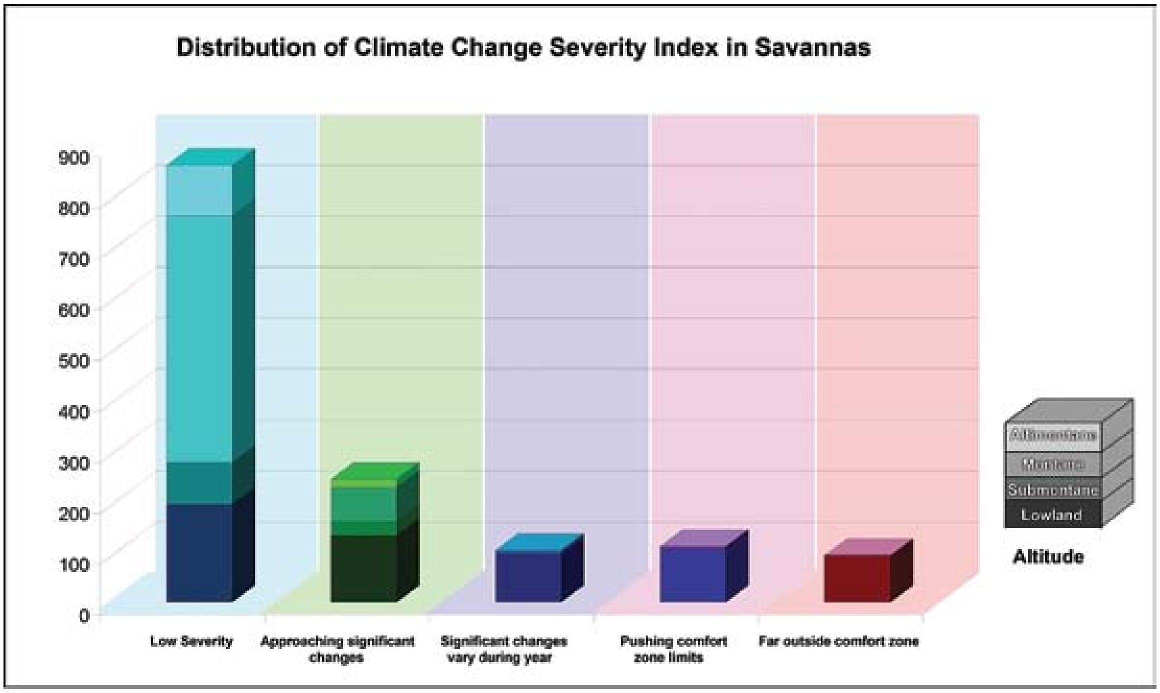
Given these remarks, the following histograms are intended to elaborate on the general conclusions drawn upon from the different climate change severity measurements at the ecosystem level. One should be able to infer the differences between the severity of climate change among the types of vegetation (or cover) and for different elevations.

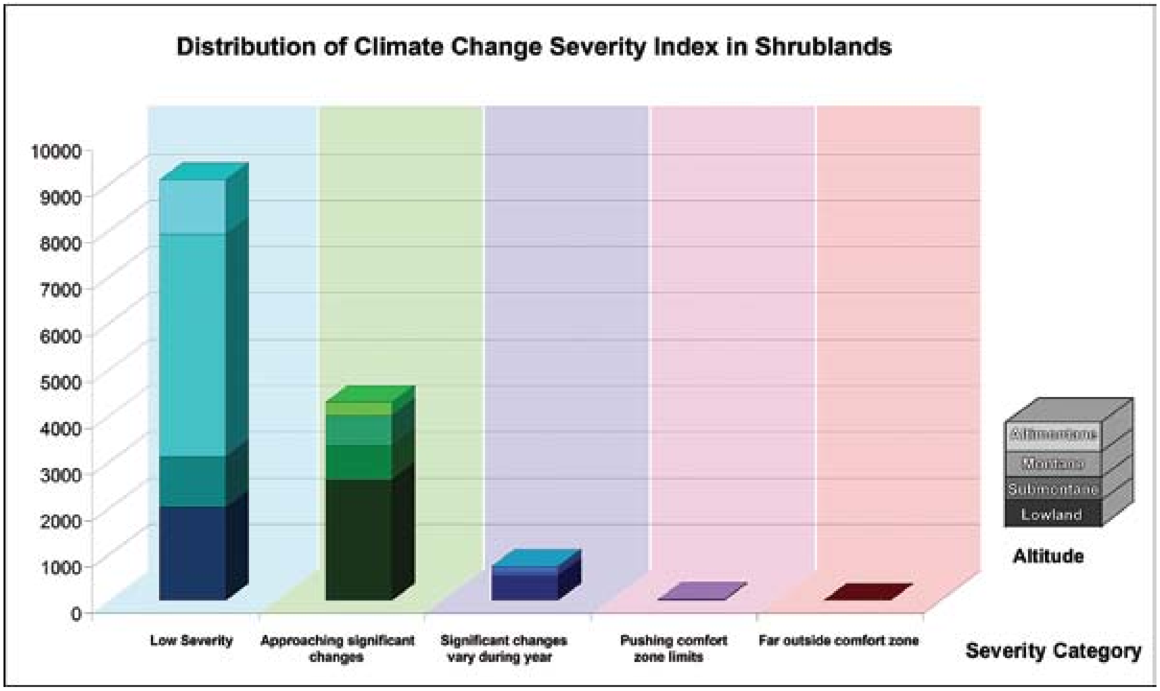

Distribution of Climate Change Severity Index in Broadleaf Forests
2500
2000
1500
1000
500
0
Low Severity
Approaching significant changes
Significant changes vary during year
Pushing comfort zone limits
Far outside comfort zone
Severity Category
Altimontane
Montane
Submontane
Lowland
Altitude

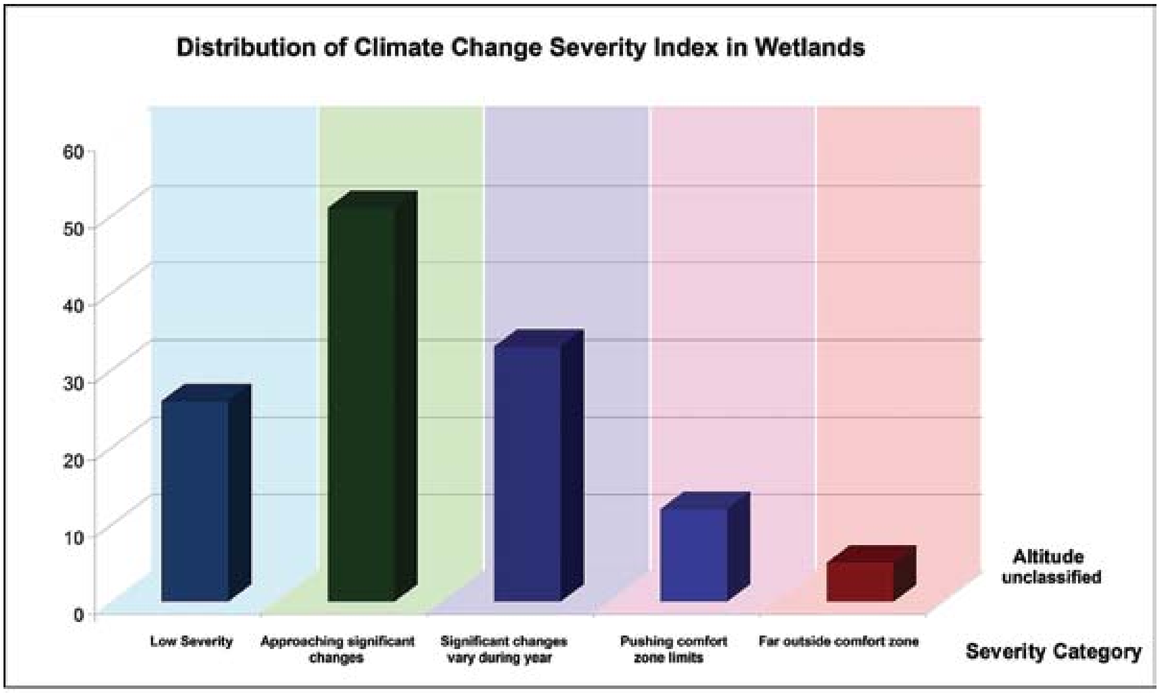

Distribution of Climate Change Severity Index in Coniferous Forests
140
120
100
80
60
40
20
0
Low Severity
Approaching significant changes
Significant changes vary during year
Pushing comfort zone limits
Far outside comfort zone
Severity Category
Altimontane
Montane
Submontane
Lowland
Altitude

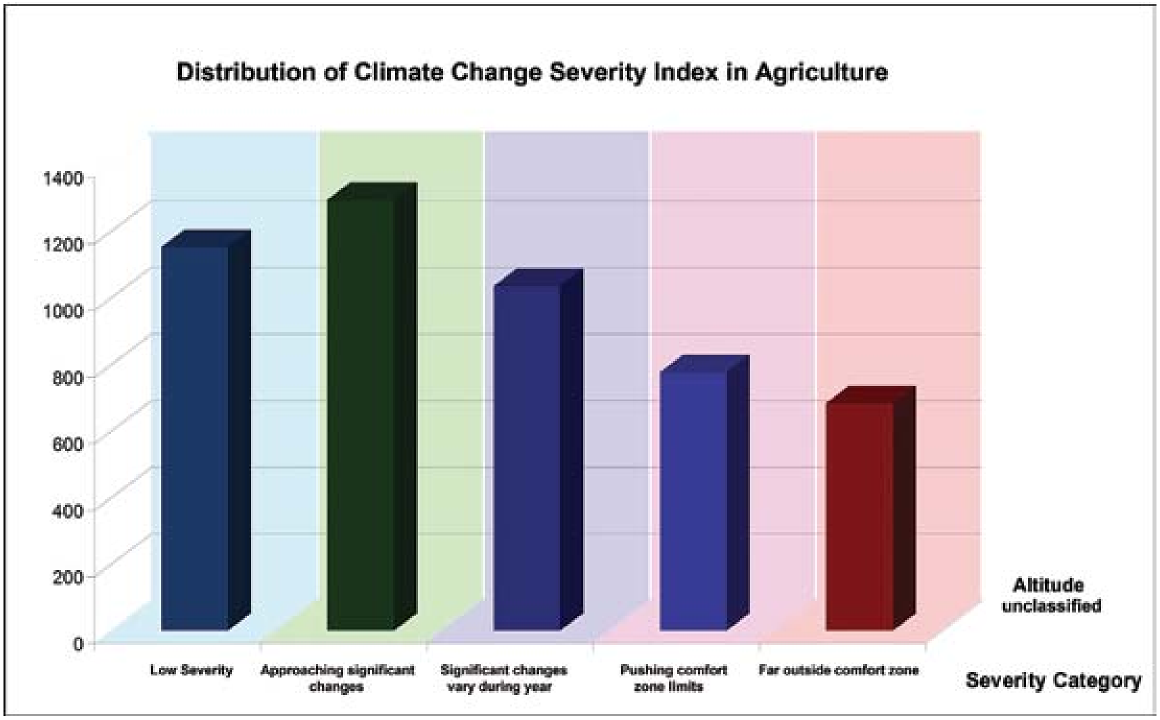

Distribution of Climate Change Severity Index in Mixed forests
350
300
250
200
150
100
50
0
Low Severity
Approaching significant changes
Significant changes vary during year
Pushing comfort zone limits
Far outside comfort zone
Severity Category
Altimontane
Montane
Submontane
Lowland
Altitude


Distribution of Climate Change Severity Index in Mangroves
50
45
40
35
30
25
20
15
10
5
0
Low Severity
Approaching significant changes
Significant changes vary during year
Pushing comfort zone limits
Far outside comfort zone
Severity Category
Altitude unclassified


Distribution of Climate Change Severity Index in Savannas
900
800
700
600
500
400
300
200
100
0
Low Severity
Approaching significant changes
Significant changes vary during year
Pushing comfort zone limits
Far outside comfort zone
Altimontane
Montane
Submontane
Lowland
Altitude


Distribution of Climate Change Severity Index in Shrublands
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Low Severity
Approaching significant changes
Significant changes vary during year
Pushing comfort zone limits
Far outside comfort zone
Severity Category
Altimontane
Montane
Submontane
Lowland
Altitude

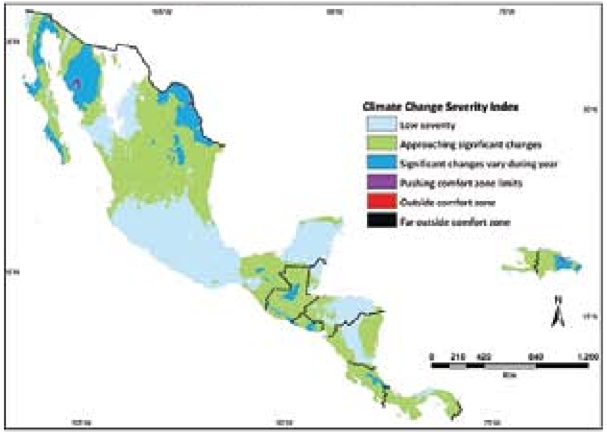

Distribution of Climate Change Severity Index in Wetlands
60
50
40
30
20
10
0
Low Severity
Approaching significant changes
Significant changes vary during year
Pushing comfort zone limits
Far outside comfort zone
Altitude unclassified
Severity Category


Distribution of Climate Change Severity Index in Agriculture
1400
1200
1000
800
600
400
200
0
Low Severity
Approaching significant changes
Significant changes vary during year
Pushing comfort zone limits
Far outside comfort zone
Altitude unclassified
Severity Category

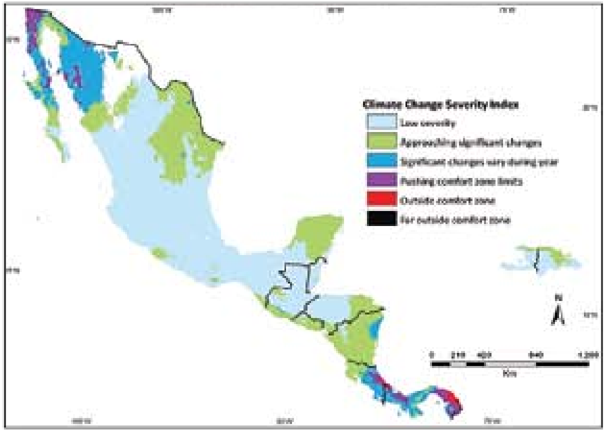
APPENDIX C: CLIMATE CHANGE SEVERITY INDEX FOR ALL SCENARIOS

This appendix provides the climate change severity index maps for all scenarios available at a resolution of 1 kilometer. These include models from the Canadian Centre for Climate Modelling and Analysis' Coupled Global Climate Model (CGCM3T47), Australia's Commonwealth Scientific and Industrial Research Organisation coupled model (CSIRO Mk3), and the United Kingdom's Hadley Centre Coupled Model, version 3 (HADCM3). For each of the three modeling organizations, we use WorldClim's downscaling for the A2 and B2 scenarios, for the time periods of 2020s, 2050s, and 2080s. This results in eighteen maps of the CCSI. The reader should be able to notice common areas of high climate change severity, especially among the 2020s, as well as how the severity spreads over time.

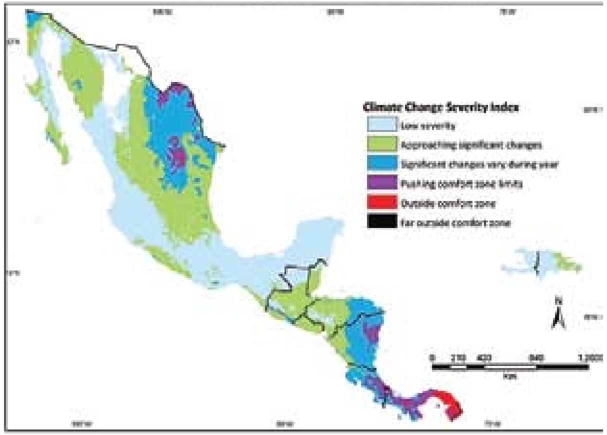
CGCM3T47 2020s: B2 scenario



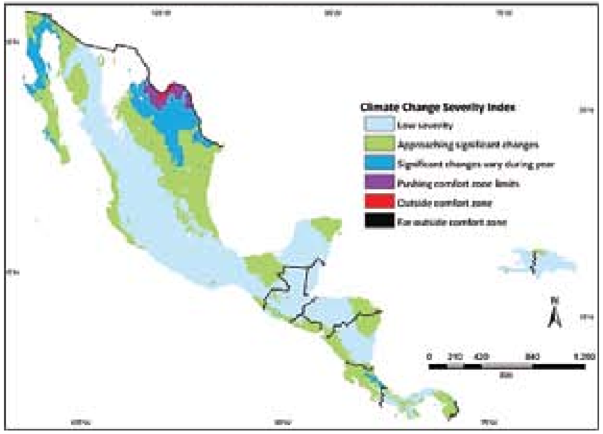
CGCM3T47 2050s: B2 scenario



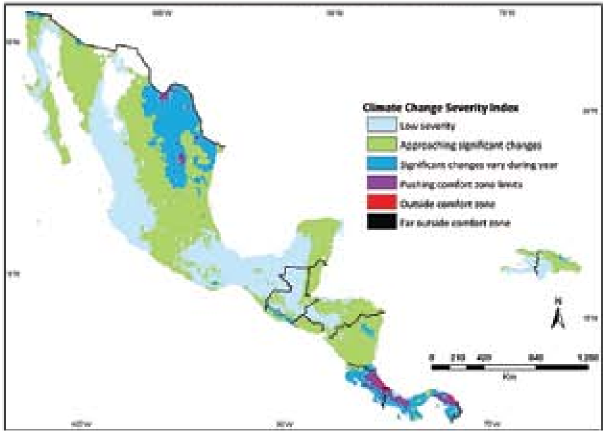
CGCM3T47 2080s: B2 scenario



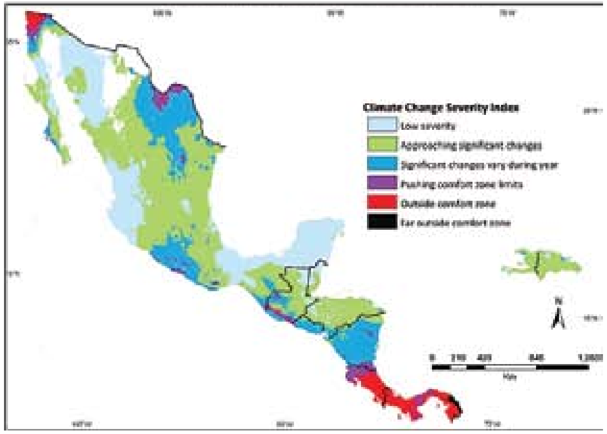
CGCM3T47 2020s: A2 scenario

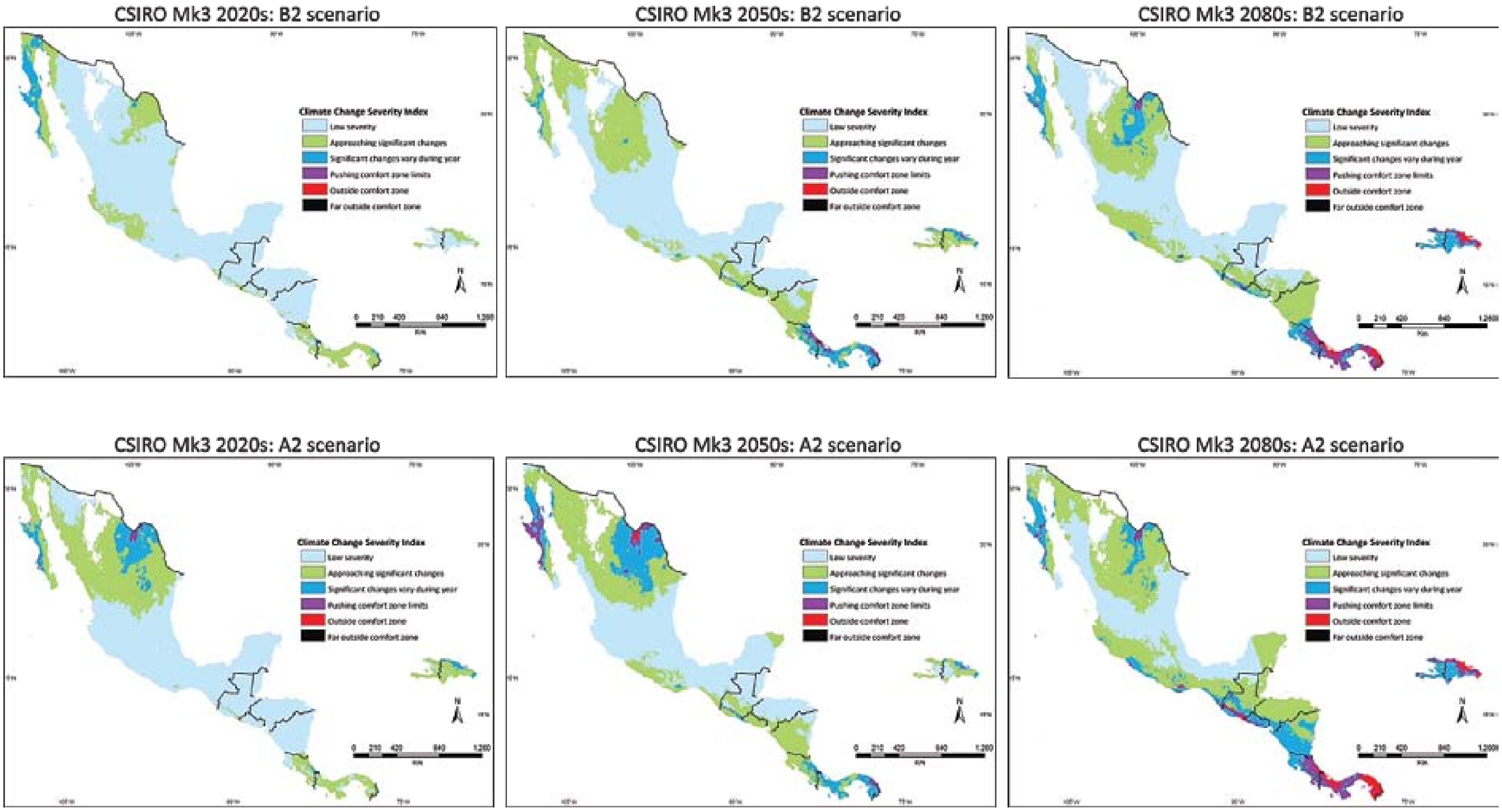


CGCM3T47 2050s: A2 scenario



CGCM3T47 2080s: A2 scenario





CSIRO Mk3 2020s: B2 scenario

CSIRO Mk3 2050s: B2 scenario

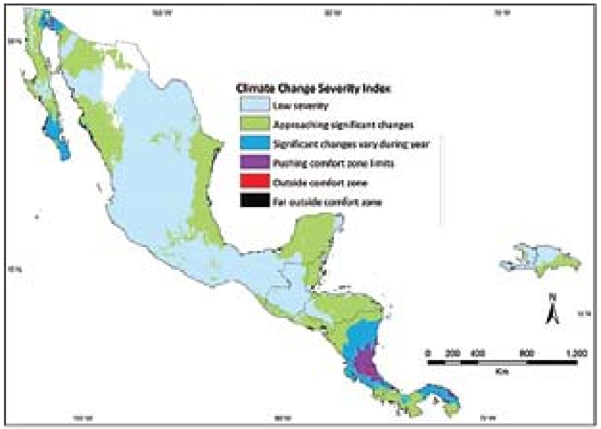
CSIRO Mk3 2080s: B2 scenario

CSIRO Mk3 2020s: A2 scenario

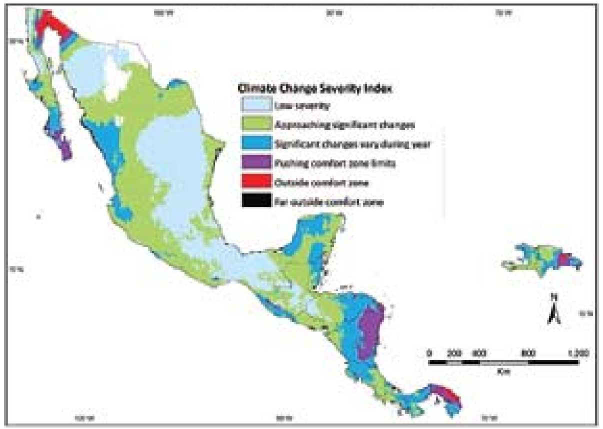
CSIRO Mk3 2050s: A2 scenario

CSIRO Mk3 2080s: A2 scenario

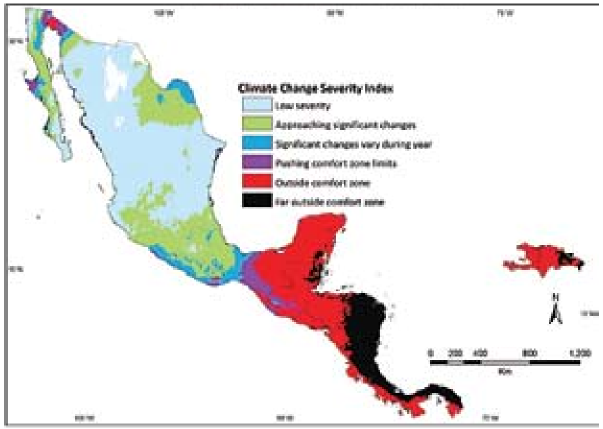
HadCM3 2020s: B2 scenario



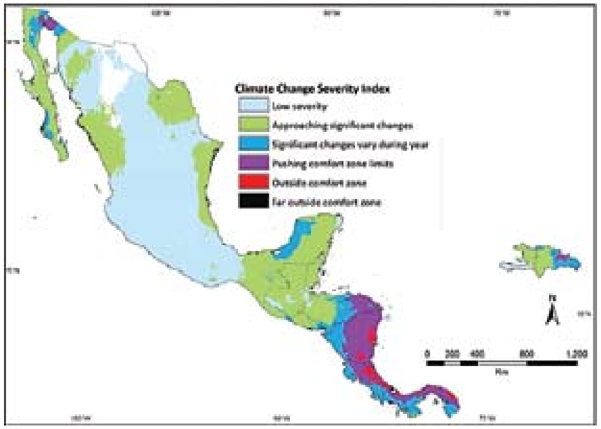
HadCM3 2050s: B2 scenario



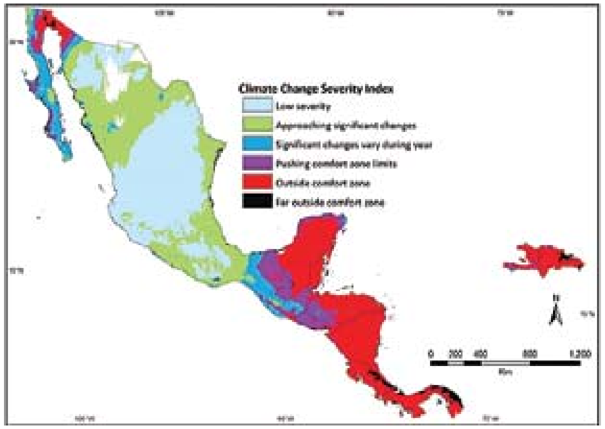
HadCM3 2080s: B2 scenario



HadCM3 2020s: A2 scenario



HadCM3 2050s: A2 scenario



HadCM3 2080s: A2 scenario