INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **34**: 2957–2971 (2014)
Published online 13 January 2014 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3889

Changes in extreme temperature and precipitation in the Caribbean region, 1961–2010

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ABSTRACT: A workshop was held at the University of the West Indies, Jamaica, in May 2012 to build capacity in climate data rescue and to enhance knowledge about climate change in the Caribbean region. Scientists brought their daily observational surface temperature and precipitation data from weather stations for an assessment of quality and homogeneity and for the calculation of climate indices helpful for studying climate change in their region. This study presents the trends in daily and extreme temperature and precipitation indices in the Caribbean region for records spanning the 1961–2010 and 1986–2010 intervals. Overall, the results show a warming of the surface air temperature at land stations. In general, the indices based on minimum temperature show stronger warming trends than indices calculated from maximum temperature. The frequency of warm days, warm nights and extreme high temperatures has increased while fewer cool days, cool nights and extreme low temperatures were found for both periods. Changes in precipitation indices are less consistent and the trends are generally weak. Small positive trends were found in annual total precipitation, daily intensity, maximum number of consecutive dry days and heavy rainfall events particularly during the period 1986–2010. Correlations between indices and the Atlantic multidecadal oscillation (AMO) index suggest that temperature variability and, to a lesser extent, precipitation extremes are related to the AMO signal of the North Atlantic surface sea temperatures: stronger associations are found in August and September for the temperature indices and in June and October for some of the precipitation indices.

KEY WORDS Caribbean; climate change; climate extreme; daily temperature; daily precipitation; trends; Atlantic multidecadal oscillation

Received 3 May 2013; Revised 1 November 2013; Accepted 12 November 2013

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1. Introduction

Small island states like those in the Caribbean have long been identified as being among the most vulnerable to climate change and climate extremes (IPCC, 2007; IPCC, 2012). This is often attributed to limited natural and human resources, restricted lands, densely populated urban and coastal areas, economic dependence on international funders and heavy reliance on fragile sectors such as tourism (Sahay, 2005; Pulwarty *et al.*, 2010; Simpson *et al.*, 2010; IPCC, 2012). Caribbean islands are attempting to address their high vulnerability and low adaptive capacity at the local (parish and community) and regional levels via a number of projects financed using adaptation funds (e.g. UNDP GEF Small Grants Programme). Fundamental to the framework however is characterizing trends in climate extremes across the region in the recent past and making projections towards the middle to end of century. This article focuses on trends in climate extremes over the Caribbean for the past 50 years.

The first regional analysis of rainfall and temperature extremes for the Caribbean was undertaken in 2001 at a workshop supported by the World Meteorological Organization (WMO) and the National Oceanic and Atmospheric Administration (NOAA) (Peterson *et al.*, 2002). Some of the results (based on 30 stations across the region) suggest that over the 1958–1999 period there has been a dramatic increase in the number of very warm days and nights, a decrease in the number of very cool days and nights, a decrease in the maximum number of consecutive dry days (CDD) and an increase in the number of heavy rainfall events for a mean Caribbean. The workshop marked the first in a series of climate change workshops held globally using the WMO Commission for Climatology (CCI) and the World Climate Research Programme (WCRP) Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI) format and modelled on the Asia Pacific Network workshops (Manton *et al.*, 2001). Similar workshops have been held for example, in countries in the western Indian Ocean (Vincent *et al.*, 2011), South America (Aguilar *et al.*, 2005; Vincent *et al.*, 2005; Haylock *et al.*, 2006; Skansi *et al.*, 2012), parts of Africa (New *et al.*, 2006; Aguilar *et al.*, 2009), the Middle East (Zhang *et al.*, 2005), Central and South Asia (Klein Tank *et al.*, 2006), Southeast Asia and South Pacific (Griffiths *et al.*, 2005; Caesar *et al.*, 2011) and the Arab region (Donat *et al.*, 2013a). An overview of the format and progress of the regional workshops are presented in Peterson and Manton (2008). These workshops provide a consistent methodology for studying extremes across the world and results may be seamlessly aggregated in global analyses as performed by Alexander *et al.* (2006) and Donat *et al.* (2013b).

Other studies on climate trends for the Caribbean indicate a modest but statistically significant drying trend for the Caribbean's summer period in recent decades (Neelin *et al.*, 2006); annual rainfall totals declining by 250 mm since 1900 (Nurse and Sem, 2001); decreasing early and late season precipitation (see Section 2) with marked negative trend commencing in 1960 (Taylor *et al.*, 2002); declining rainfall in the central Caribbean with an increasing trend in stations in Nassau and Maracaibo (Aparicio, 1993; Singh, 1997; Walsh, 1998; Martin and Weech, 2001); an increase in temperature exceeding 0.5 °C since 1900 (Nurse and Sem, 2001). Similar trend analyses have been conducted for Cuba and suggest an increase in annual mean temperatures by nearly 0.5 °C; an increase in the frequency of intense rains and local storms; increase in winter rainfall but decrease in summer; increase in frequency of droughts and diminished landfall hurricane activity in the latter half of the 20th century (Naranjo and Centella, 1998; Lapinel *et al.*, 2002; Álvarez, 2006). See reviews in Gamble and Curtis (2008) and Chen *et al.* (2008).

This article presents results from the second climate change workshop hosted in the Caribbean at the University of the West Indies on May 7–10, 2012. The workshop aimed to build capacity in historic data rescue and investigating and quantifying climate change effects and impacts. It was an important follow up to the 2001 workshop as it allowed 30 meteorologists and climate scientists from the region to explore trends in extreme precipitation and temperature with over a decade's worth more data than available in 2001. Additionally, the second workshop exploited an expanded suite of extreme indices and improved software for evaluating homogeneity and calculating indices. This article examines trends in daily and extreme temperature and precipitation over the Caribbean for two periods: 1961–2010 and 1986–2010. For each period, trends are presented spatially and temporally. The temporal representations exploit regionally averaged indices following distinct subregions identified by Jury *et al.* (2007): Section 2 provides further rationale and description of the subregions. Additionally, Caribbean-wide averaged series is presented for comparison with Peterson *et al.* (2002) results and to investigate the representativeness of region-wide indices with respect to those derived subregionally. The approach is an important one as it represents to date the most detailed spatial representation of observational climate trends for the Caribbean region and allows the investigation of subregional variations. Finally, the relationship between the indices and the Atlantic multidecadal oscillation (AMO) index is examined in order to better understand the temperature and precipitation temporal variability over the Caribbean region.

2. Caribbean's regions

The Caribbean Basin includes a diverse collection of nations that encompasses both large (Greater Antilles) and small (Lesser Antilles) islands as well as coastlines along Central and South America. The general climate of the Caribbean can be described as *dry-winter tropical* (Rudloff, 1981) with an associated bimodal seasonal rainfall pattern. This bimodality divides the rainfall pattern

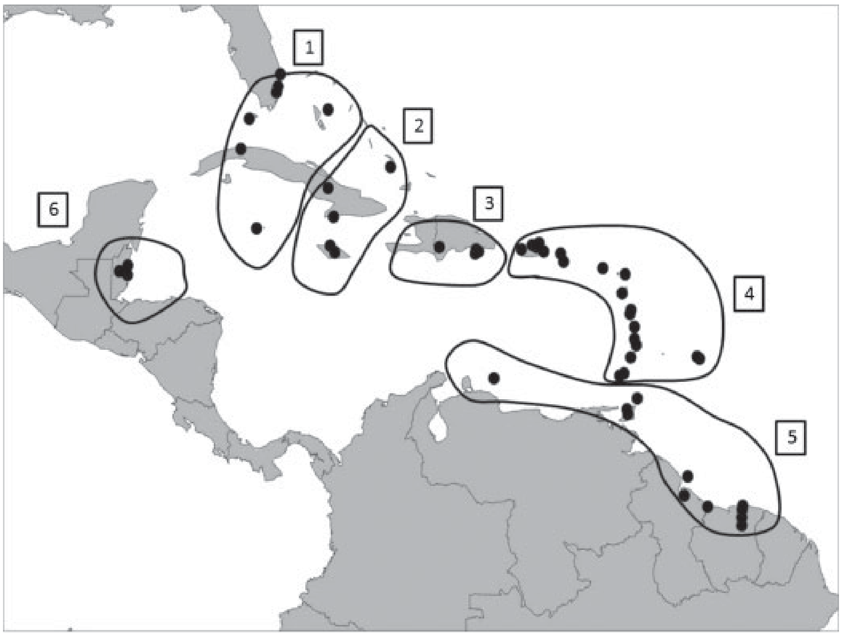


Figure 1. Location of the 51 stations divided into six regions.

into an early (April–July) and a late (August–November) rainfall season (Chen and Taylor, 2002). The relative minimum between the early and late rainfall season has many regional names such as *Petit Carême* (Trinidad and Tobago), *le carême* (Guadeloupe, Martinique), *la canicula* (Mexico) or *el veranillo* (Costa Rica), but is known in general as the mid-summer drought (MSD) throughout the Intra-American Sea (Magana *et al.*, 1999; Giannini *et al.*, 2000; Curtis, 2002; Mapes *et al.*, 2005). This seasonal tendency differs along the southernmost regions of the Caribbean where areas such as Venezuela and the Dutch Antilles experience a winter rainfall maximum (Martis *et al.*, 2002).

Despite the overall presence of an early and late rainfall season separated by the MSD, regions of distinct sub-basin scale rainfall variation exist. Regional variability is present in annual totals, length of the rainy season and length and timing of the MSD. Previous research has made numerous efforts to subdivide the Caribbean Basin into regions with similar rainfall patterns using various techniques (Giannini *et al.*, 2000; Chen and Taylor, 2002; Curtis and Gamble, 2007; Gamble *et al.*, 2007). More recently, Jury *et al.* (2007) used factor analysis to create spatial clusters with orthogonal time scores. This results in a four factor solution subdividing the Caribbean Basin into four distinct zones that are distinguished from one another by their seasonal rainfall cycle and its timing.

The focus of our analysis attempts to capture the regional variability within the Caribbean Basin by treating the analysis in defined regions. By doing this, we avoid describing a generalized and potentially misleading coarse Caribbean rainfall regime, while respecting and utilizing prior successful research efforts. This attempt has been completed by Jury (2009) and Charlery *et al.* (2006) who analyse rainfall data within the Caribbean in defined regions. However for comparative purposes, the analyses presented in this study also examine results averaged across the entire Caribbean domain. Figure 1 presents the six regions: the four regions as defined by Jury *et al.* (2007) and two additional regions (regions 5 and 6) which accommodate other stations used in our study but outside of the area analysed by Jury *et al.* (2007).

3. Data and methodologies

Workshop participants brought daily maximum and minimum temperature and precipitation data for 51 stations across the Caribbean and neighbouring countries. Data records varied in length across all the locations with some stations having only precipitation or maximum and minimum temperatures. Stations used in this study are listed in Table 1. Figure 1 shows their locations. Sufficient data were compiled to undertake analyses over two periods: our primary period 1961–2010 and a secondary period 1986–2010 which allowed the inclusion of more stations. Though a great deal of the analyses was performed during the workshop, these were revisited subsequent to the workshop to ensure robustness of the results.

As the Caribbean region consists mostly of small island developing States and other developing nations, not all public weather services can maintain a climatology department. For that reason, it has frequently been a challenge to maintain consistency and continuity in time series of daily weather observations and accompanying metadata (Peterson *et al.* 2002). An additional challenge in keeping good records is the necessary conversion to digital databases for most climatological

Table 1. List of stations with homogeneity results.

Country	Station name	Latitude (°N)	Longitude (°W)	Period		Zone	Detected steps[a]
				Start	End		
Antigua and Barbuda	V.C Bird International Airport	17.1	61.5	1969	2011	4	
Bahamas	Nassau	25.0	77.5	1961	2011	1	
Barbados	CIMH	13.2	59.6	1969	2010	4	
	Grantley Adams International Airport	13.1	59.5	1971	2011	4	
Belize	Belmopan	17.3	88.8	1974	2010	1	
	Central Farm	17.2	88.3	1966	2011	1	
	Philip Goldson Airport	17.5	88.3	1960	2010	1	
Cayman	Owen Robert A Georgetown	19.3	81.4	1976	2010	2	
Cuba	Cabo	19.9	77.2	1980	2012	2	
	Camagüey	21.2	77.5	1961	2012	2	↓TX 1973
	Casablanca	23.1	82.2	1961	2012	1	
	Maisi	22.3	74.2	1980	2012	2	
Curaçao	Hato	12.1	68.6	1992	2011	5	↓TX TN 2001
Dominica	Canefield Airport	15.2	61.2	1982	2010	4	↓TN 2005
	Melville Hall Airport	15.3	61.2	1975	2010	4	
Dominican Republic	Jimani	18.3	71.5	1971	2010	3	
	La Romana	18.3	69.6	1924	2012	3	
	Las Americas	18.3	69.4	1971	2011	3	
	Santo Domingo	18.3	69.5	1971	2011	3	
Grenada	Maurice Bishop International Airport	12.3	61.6	1986	2010	4	
	Point Salines	12.3	61.8	1989	2010	4	
	Point Salines	12.3	61.8	1985	2005	4	
Guadeloupe	Petit-bourg	16.2	61.7	1969	2006	4	↑TX 2001
Guyana	George Town	6.5	58.1	1962	2007[b]	5	
	Timehri	6.5	58.3	1981	2010	5	
Jamaica	Discovery Bay Maine Lab	18.5	77.4	1992	2009[c]	2	
	Worthy Park	18.2	77.2	1973	2011	2	↓TN 2003
Martinique	Lamentin	14.6	61.0	1953	2011	4	↑TX 1996
Puerto Rico	Colosso	18.5	66.5	1905	2011[d]	4	↑TN 2002
	Manati 3E	18.3	66.3	1900	2011[d]	4	↓TX 1985
	Maunabo	18.0	65.9	1960	2003[e]	4	
	Mayaguez City	18.1	67.1	1900	2011[d]	4	
	San Juan	18.5	66.1	1977	2011	4	
Saint Lucia	GFL Charles Airport	14.0	61.0	1989	2010	4	
	Hewanorra	13.7	60.9	1973	2009	4	↓TN 2004
St Kitts and Nevis	St Kitts (sugar factory)	17.3	62.7	1981	2007	4	
St Vincent and the Grenadines	E. T. Joshua Airport	13.1	61.2	1986	2012	4	
Suriname	Cultuurtuin	5.8	55.2	1971	2010	5	
	Nickerie	6.0	57.0	1971	2010	5	
	Lelydorp	5.1	55.2	1911	2010[e]	5	
	Zanderij	5.5	55.2	1971	2011	5	↓TX 1996
	Zorg en Hoop	5.8	55.2	1971	2010	5	↑TX 2007
Trinidad and Tobago	Crown Point	11.2	60.8	1967	2012	5	
	Piarco	10.6	61.3	1960	2012	5	
	St Augustine	10.6	61.4	1969	2010	5	
USA Florida	Fort Lauderdale	26.1	80.2	1948	2010	1	
	Key West WSO Airport	24.6	81.8	1948	2010	1	
	Miami WSCMO Airport	25.8	80.3	1948	2010	1	
	West Palm Beach	26.7	80.1	1948	2010	1	
Virgin Islands	Christiansted Hamilton Airport	17.7	64.8	1951	2010	4	↓TX 2000
	Charlotte Amalie Cyril E King Airport	18.3	65.0	1953	2010	4	↓TX 1996

[a] Arrow pointed up (down) indicates increasing (decreasing) step; TX (TN) indicates maximum (minimum) temperature; date of detected step. [b] For precipitation, the period is 1954-2010. [c] For precipitation, the period is 1992-2011. [d] No data for precipitation. [e] No data for temperature.

analyses. Therefore, a necessary precursor to the calculation of climate indices is thorough quality control (QC) and assessment of data homogeneity to eliminate erroneous daily rainfall (RR), minimum temperature (TN) and maximum temperature (TX) as well as to identify artificial jumps in the time series. To ensure consistency with similar regional climate extreme trends studies, we therefore used the RClimDex (version 1.0) QC and RHTests (version 3.0) data homogenization tools provided by the Expert Team on Climate Change Detection and Indices (ETCCDI). Software and documentation are available at http://etccdi.pacificclimate.org.

3.1. Data quality

With RClimDex, station records were corrected for errors in RR (negative values), and in TX and TN (TN higher or equal to TX). Erroneous RR values were always replaced with missing values. Similarly, errors pertaining to highly improbable values of either TX or TN or both were removed. However, in several instances, it was apparent that (1) TX and TN were swapped; (2) an erroneous TX value was likely the correct TN value or opposite; and (3) a digitisation error occurred, e.g. misreading of the first of two digits before the decimal point, or decimal point misplaced. In such cases, the actual erroneous value was replaced with its realistic value as identified from the climatology.

In addition, RClimDex detects outliers in RR, TX and TN based on user-defined thresholds. In this study, we defined an upper RR threshold of 300 mm which, in most of the Caribbean region, represents values that are very rare and typically only exceeded in case of direct impact by a tropical cyclone or when cool fronts meet unstable and moist trade winds. For TX and TN, a 5 standard deviation (5σ) threshold was defined. The latter is calculated for each individual day of the year based on values recorded in all years to detect outliers. Local climatological expertise was used to assess whether outliers were likely extreme values or artefacts. Outliers identified as artefacts were subsequently replaced with missing values in the observed data time series.

Finally, upon completion of the RClimDex-based QC, visual inspection of TN and TX time series was performed to identify residual artefacts, namely seemingly unrealistically low or high values that fall within 5σ. The rationale was that a given season may show substantially reduced variability compared to the same season in other years – meaning a reduced chance of 5σ outliers – though physically highly improbable values are still found, e.g. a TN of 32 °C in St Kitts in October. Such values were removed if erroneous beyond any reasonable doubt.

For this study, amongst all 51 stations and their complete period of data, less than 1% of the daily temperatures and less than 0.1% of the daily rainfall were corrected for errors and outliers.

3.2. Data homogeneity

Relocation of instruments and changes in observing procedures can sometimes introduce non-climatic shifts in climate time series and these shifts can influence the proper assessment of any climate trends (Aguilar *et al.*, 2003; Trewin, 2010; Vincent *et al.*, 2012). Homogeneity assessment can be complex since it requires long records of observations, close neighbour stations and detailed station history (metadata) in order to determine the cause of the detected shifts. Climate data homogenization in the Caribbean region is difficult because the stations are far from each other, they often belong to different climate regimes and they cover various periods and short periods of time (Figure 1 and Table 1). In addition, metadata are often sparse or non-existent for many stations in this region.

In this study, the time series of the monthly mean temperature anomalies derived from TX and TN separately were examined for temporal homogeneity using the RHTests software package (Wang and Feng, 2009). The procedure consists of detecting shifts in the difference between the time series of the monthly mean temperature anomalies of a candidate station and those of a neighbour station. The procedure was applied using four different neighbours separately. Although many shifts are identified using this procedure, only common shifts (same dates identified by at least two neighbours) were retained and further analysed.

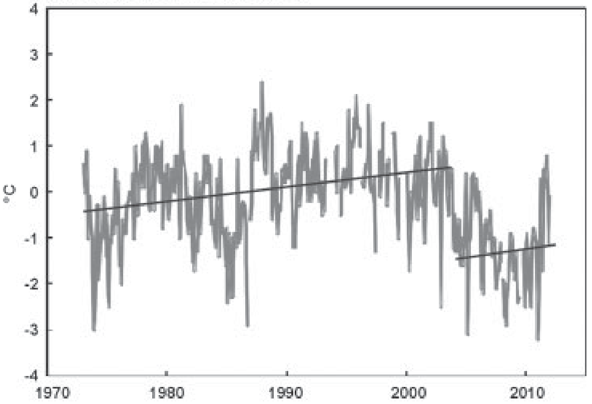
The results are presented in Table 1. Altogether, only 14 shifts were investigated. The shifts were found in either TX or TN; only the station from Hato (Curaçao) has a decreasing step in 2001 in both TX and TN. The results also indicate that 10 shifts were decreasing steps and that 9 shifts occurred in the 2000s. No potential causes were identified in order to explain the detected shifts and it is possible that the shifts were simply due to climate variations. No adjustments were applied to the data at this time and only the longest homogeneous period was used for trend analysis. As an example, Figure 2 shows a decreasing shift in the anomalies of the monthly mean of TN in 2003 at Worthy Park (Jamaica) and in 2004 at Hewanorra (Saint Lucia). It will be possible to determine if these shifts will continue in time when additional observations become available.

Detection of inhomogeneities in precipitation time series is more difficult due to the high variability of the precipitation time and distance between neighbouring stations. Applying RHTests procedure on the log transformation of the wet months did not reveal inhomogeneities for any of the stations.

3.3. Indices

In addition to detecting outliers, RClimdex facilitates the calculation of a suite of 27 climate indices. In this study, a subset of 21 indices were investigated as they were considered relevant to the Caribbean and adjacent regions (see Table 2 for a complete description). The indices are made available to the international scientific community via the ETCCDI website (http://etccdi.pacificclimate.org/data.shtml) for climate variability and monitoring and are of lower commercial value than the raw data from which they are derived. Of the 21 indices presented in this study, 11 relate to temperature and include annual means and cool and warm extremes. Some of the extreme temperature indices are percentile based. Warm days (nights) are defined as annual or monthly count (indicated with superscript letter ‘a’ in Table 2) when maximum (minimum) temperature is greater than the 90th percentile; conversely, cool days (nights) are the annual count when maximum (minimum) temperature is less than the 10th percentile. The 90th and 10th percentiles are calculated

(a) Worthy Park, Jamaica



(b) Hewanorra, Saint Lucia

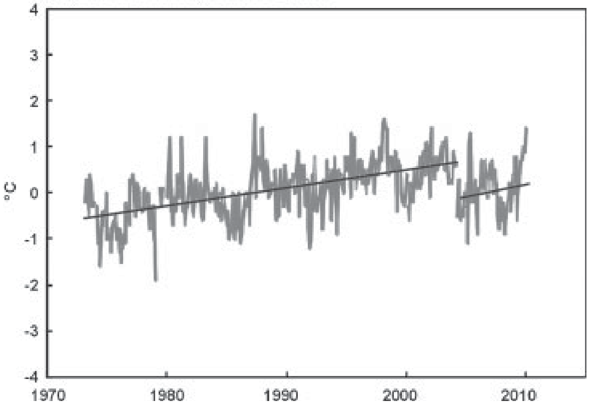


Figure 2. (a) Step identified in 2003 in the monthly mean anomalies of the daily minimum temperature of the station Worthy Park, Jamaica; (b) step identified in 2004 in the monthly mean anomalies of the daily minimum temperature of the station Hewanorra, Saint Lucia.

using a 5-day window centred on each calendar day over the reference period 1971–2000 (for the stations with shorter record, the percentiles were calculated over the period defined by the beginning year of the record to 2000). Extreme temperatures such as the highest/lowest daily values during the year or month were also investigated. In this study, 10 precipitation indices that relate to intensity, frequency and duration are analysed. They include the maximum number of CDD and consecutive wet days (CWD) (daily rainfall below and above 1 mm, respectively) observed yearly and the number of days with daily rainfall above 10, 20 and 50 mm. The annual total precipitation (PRCPTOT) was divided by the average total precipitation over 1971–2000 in order to produce a series which is not dominated by very high precipitation amounts. Similarly, the annual or monthly highest daily precipitation (RX1day), highest 5 consecutive days precipitation amount (RX5day) and heavy rainfall events (R95p) were further divided by the annual total precipitation to avoid very large values (which can influence the trend estimate) and to allow each index to be included in regional averages, with each station contributing equally to the average. Annual indices were computed if no more than 15 days were missing during the year, and percentiles were calculated if no more than 20% values were missing in the reference period.

3.4. Regional average indices

Subregional variations in precipitation and temperature over the Caribbean and neighbouring regions are represented using an average series calculated for each index over each of six regions shown in Figure 1 and indicated in Table 1. To account for the different periods covered by each station and the spatial distribution of the stations, anomalies from the 1981–2000 common reference period were first obtained at each station, and were then averaged over each of the six regions and also for the entire Caribbean area and adjacent countries. Regional average indices were calculated using stations having less than 30% of missing values in the analysed periods.

3.5. Trend estimation

Linear trends for individual stations and regional average series were fitted using the ordinary least squares regression. The trends were calculated for 1961–2010 and the shorter period 1986–2010. Although a period of 25 years is small for detecting any climate change signal, it allows for the inclusion of more stations in the analyses. The trends were computed only if more than 80% of the values were present in the time series. The statistical significance of the trends was assessed at the 5% level using the t-test.

4. Results

The results show consistent changes in the temperature and precipitation indices during the past 50 and 25 years in the countries and territories of the Caribbean region. However, the changes in temperature indices have a better spatial coherence than those found in the precipitation indices due to higher spatial and temporal variability in precipitation as compared to temperature. Table 3 presents the trends (index units/10 years) for the entire Caribbean region and adjacent countries for 1961–2010 and 1986–2010.

4.1. Temperature means

The analyses of the annual mean of daily maximum temperature (TXmean) suggest a general warming of the daytime temperature over the 1961–2010 period (Figure 3). TXmean Caribbean-wide regional average indicates a significant warming of $0.19\,^{\circ}\mathrm{C\,decade}^{-1}$ (Table 3). The annual mean of daily minimum temperature (TNmean) suggest a significant and more pronounced warming of $0.28\,^{\circ}\mathrm{C\,decade}^{-1}$ over the same period. Nighttime temperature (TNmean) trends at individual stations are generally greater than daytime temperature (TXmean) trends. This difference leads to a decrease in diurnal temperature range (DTR). Significant increasing DTR trends are evident only at Key West (Florida) and Georgetown (Guyana) over the 1961–2010 period.

Table 2. Definition of the temperature and precipitation indices (computed on annual basis) used in this study. TX, TN and RR are daily maximum temperature, minimum temperature and total rainfall, respectively.

Element	Index	Descriptive name	Definition	Unit
Temperature	TXmean[a]	Annual maximum temperature	Annual mean of TX	°C
	TNmean[a]	Annual minimum temperature	Annual mean of TN	°C
	DTR[a]	Diurnal temperature range	Annual mean difference between TX and TN	°C
	TX90P[a]	Warm days	Percentage of days when TX > 90th percentile	%
	TX10P[a]	Cool days	Percentage of days when TX < 10th percentile	%
	TN90P[a]	Warm nights	Percentage of days when TN > 90th percentile	%
	TN10P[a]	Cool nights	Percentage of days when TN < 10th percentile	%
	TXx[a]	Highest TX	Annual highest value of TX	°C
	TXn[a]	Lowest TX	Annual lowest value of TX	°C
	TNx[a]	Highest TN	Annual highest value of TN	°C
	TNn[a]	Lowest TN	Annual lowest value of TN	°C
Precipitation	PRCPTOT	Annual precipitation	Annual total precipitation	mm
	SDII	Simple daily intensity index	Annual precipitation divided by number of wet days	mm/day
	CDD	Consecutive dry days	Maximum number of consecutive dry days	days
	CWD	Consecutive wet days	Maximum number of consecutive wet days	days
	R10mm	Days above 10 mm	Annual count of days when RR > 10 mm	days
	R20mm	Days above 20 mm	Annual count of days when RR > 20 mm	days
	R50mm	Days above 50 mm	Annual count of days when RR > 50 mm	days
	RX1day[a]	Max 1-day precipitation	Annual highest daily precipitation	mm
	RX5day[a]	Max 5-days precipitation	Annual highest 5 consecutive days precipitation	mm
	R95p	Very wet days	Annual total precipitation when RR > 95th percentile	mm

[a] Indices which are also calculated on a monthly basis.

Table 3. Trends for 1961–2010 and 1986–2010 (index units/10 years) for the Caribbean region and adjacent countries calculated from annual indices.

Element	Index	1961–2010	1986–2010	Unit
Temperature	TXmean	**0.19**	**0.12**	°C
	TNmean	**0.28**	**0.22**	°C
	DTR	**−0.10**	**−0.08**	°C
	TX90P	**3.31**	**6.49**	%
	TX10P	**−1.80**	−0.08	%
	TN90P	**4.07**	**5.97**	%
	TN10P	**−2.55**	−0.76	%
	TXx	**0.27**	**0.23**	°C
	TXn	**0.18**	−0.02	°C
	TNx	**0.23**	**0.31**	°C
	TNn	**0.32**	0.23	°C
Precipitation	PRCPTOT	2.32	3.46	%
	SDII	0.16	**0.59**	mm day^{-1}
	CDD	−0.81	1.25	days
	CWD	0.25	0.22	days
	R10mm	0.90	0.68	days
	R20mm	0.46	0.82	days
	R50mm	0.21	0.44	days
	RX1day	0.03	0.18	%
	RX5day	−0.03	0.18	%
	R95p	0.95	**2.05**	%

Bold values correspond to trends significant at the 5% level.

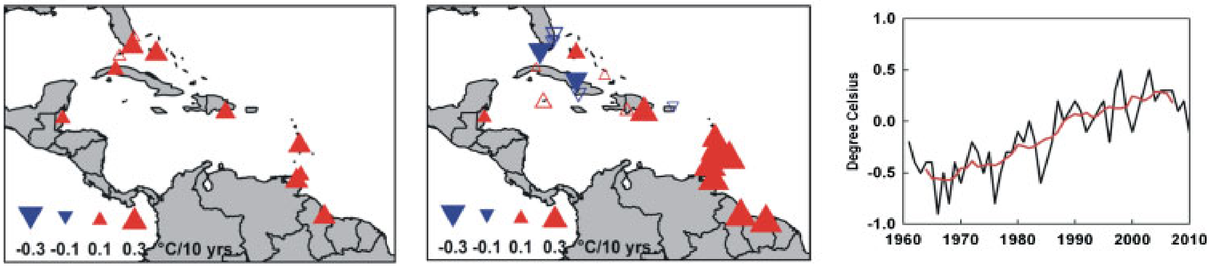
For 1986–2010, warming TXmean and TNmean trends are observed at most of the stations (Figure 3). However, a cooling of the daytime temperature is evident at several stations in Florida and Cuba (regions 1 and 2) and significant decreasing TXmean trends are found at Key West (USA) and Camagüey (Cuba). TNmean trends suggest a strong warming of the nighttime temperature. Significant decreasing trends in DTR are observed over most of the Caribbean region for 1986–2010. Increasing DTR trends are found at most Grenada and St Lucia stations and at Georgetown (Guyana) and Zorg en Hoop (Suriname). Overall, the results indicate that the Caribbean region and the adjacent countries are warming, with the signal being most robust with respect to annual mean of the daily minimum temperature.

4.2. Temperature extremes

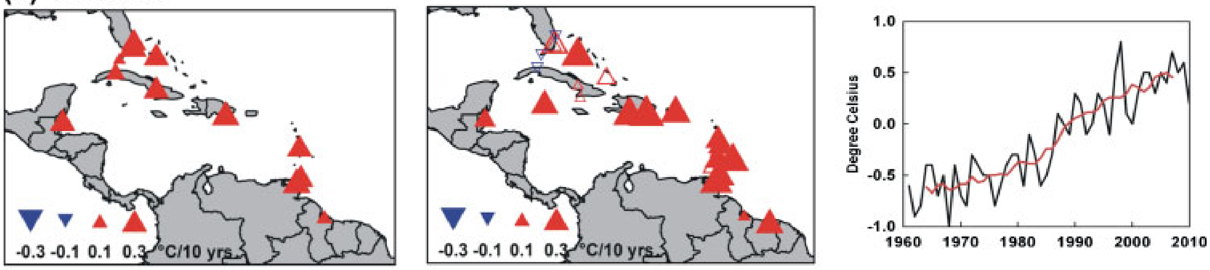
Changes in temperature extremes are spatially consistent across the Caribbean region and the adjacent countries. Overall, the results show a statistically significant increase in the frequency of extreme warm temperatures and a significant decrease in the frequency of extreme cool temperatures at most stations (Figure 4). However, changes are not symmetrical and they are more pronounced in the extreme highs than in the extreme lows. During 1961–2010, the regional average indicates that the frequency of warm days (TX90P) and warm nights (TN90P) has increased by 3.31 and 4.07% (approximately 12 and 15 days) per decade, respectively, whereas the frequency of cool days (TX10P) and cool nights (TN10P) has decreased by only 1.80 and 2.55% per decade (Table 3). Spatially, the trends at individual stations show more warm days/nights and less cool days/nights (Figure 4). The regional average time series also indicate a very high value associated with the strong El Niño year of 1998 in TX90p and TN90p.

Over the shorter period 1986–2010, the changes in the frequency of warm days and warm nights are more pronounced than for the longer period. The regional averages show a significant increase in TX90P and TN90P of 6.49 and 5.97% per decade, respectively. The spatial pattern showing fewer warm days and more cool

(a) TXmean



(b) TNmean



(c) DTR

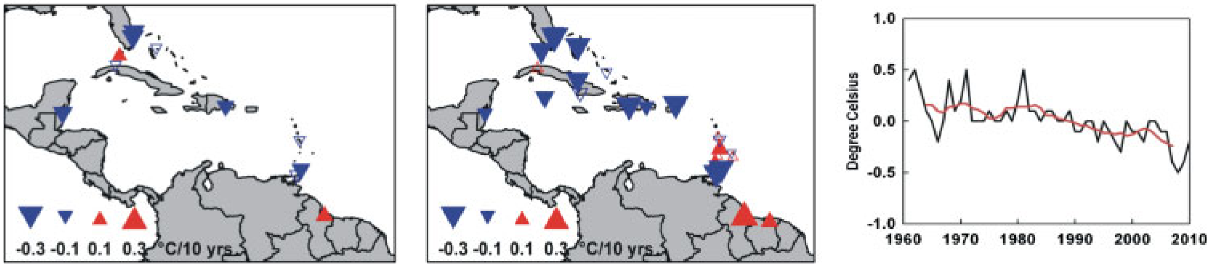


Figure 3. Trends in (a) TXmean, (b) TNmean and (c) DTR. Left panels show the trends for 1961–2010; middle panels show the trends for 1986–2010; and right panels present the time series for area averaged anomalies for 1961–2010 relative to a 1981–2000 climatology. Upward (downward) pointing triangles indicate positive (negative) trends. Solid triangles correspond to trends significant at the 5% level. The size of the triangle is proportional to the magnitude of the trend. Red colour indicates warming, blue indicates cooling trends in (a) and (b); blue colour indicates that the daily minimum is increasing more than the daily maximum in (c). The red line in the right panels is a 7-point running mean.

days in Florida and Cuba generally corresponds to the changes observed in TXmean over the past 25 years. The frequency of extreme warm nights (TN90p) has increased at all stations whereas the frequency of extreme cool nights (TN10p) has decreased at most stations during 1986–2010 (Figure 4).

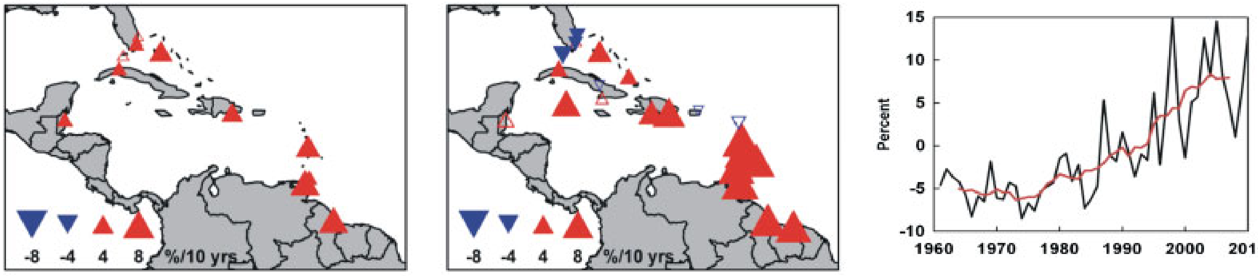
The temperatures of the warmest day (TXx) and of the warmest night (TNx) of the year have increased at most stations, with the TXx and TNx regional average indicating a change of 0.27 and 0.23 °C decade^{-1}, respectively, for 1961–2010 (Table 3). Similarly, the temperatures of the coldest day (TXn) and of the coldest night (TNn) of the year show an increase of 0.18 and 0.32 °C decade^{-1}, respectively, over the same period. Spatially, the trends are positive at most of the stations: however, a few decreasing trends are also found in TXx, TXn and TNn at some of the stations in Florida and Cuba over the shorter period 1986–2010 (figure not presented).

4.3. Precipitation total, intensity and duration

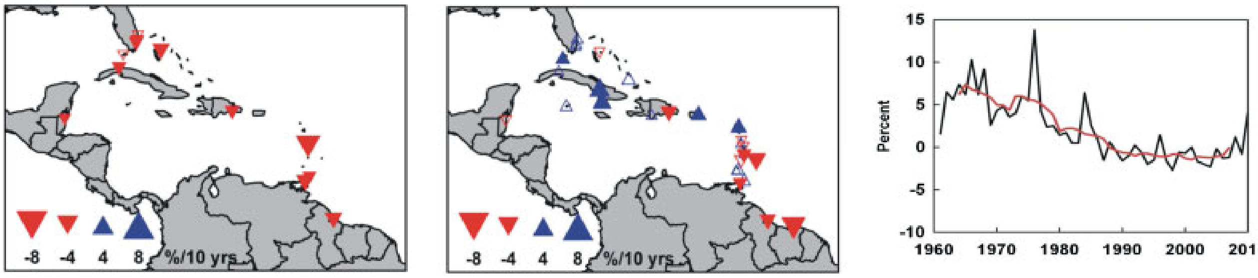
For 1961–2010, the results show no statistically significant trend in the annual total precipitation (PRCPTOT) at any location at the 5% level. Similarly, a significant increase in the simple daily intensity index (SDII) was only recorded at three stations over the past 50 years (Figure 5). In congruence, small positive trends in the annual PRCPTOT and SDII regional averages were not found to be statistically significant (Table 3). Along the same line, the annual maximum numbers of CDD and CWD have not significantly changed during 1961–2010; spatially, a mixed pattern of small non-significant positive and negative trends was found over the Caribbean region.

The trends are more pronounced locally for records spanning the shorter period 1986–2010. While no significant positive trend in PRCPTOT regional average was observed, strong and significant increases are evident at Maisi (Cuba), Crown Point (Trinidad) and Georgetown (Guyana). The most significant change was found in a rise of the daily intensity rainfall at the majority of the locations, many of which are significant. The trend indicates that when precipitation occurs, it tends to be heavier. The SDII regional average indicates a significant increase of 0.59 mm day^{-1} decade^{-1} (Table 3). In addition, significant SDII increases of 0.77, 1.03 and 1.43 mm day^{-1} decade^{-1} were found in regions 1, 2 and

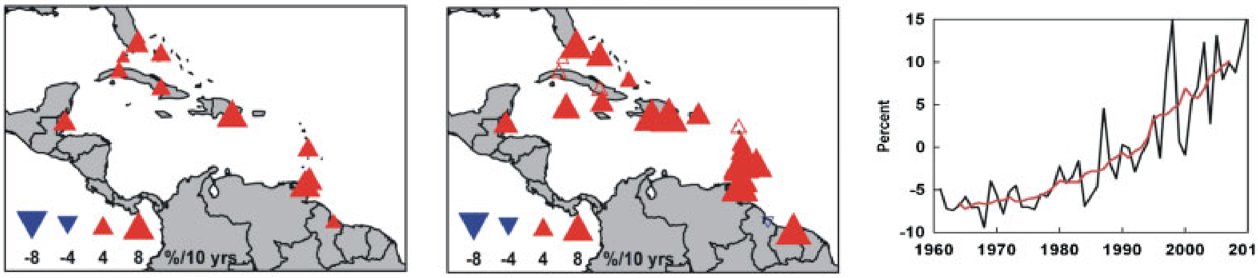
(a) TX90P



(b) TX10P



(c) TN90P



(d) TN10P

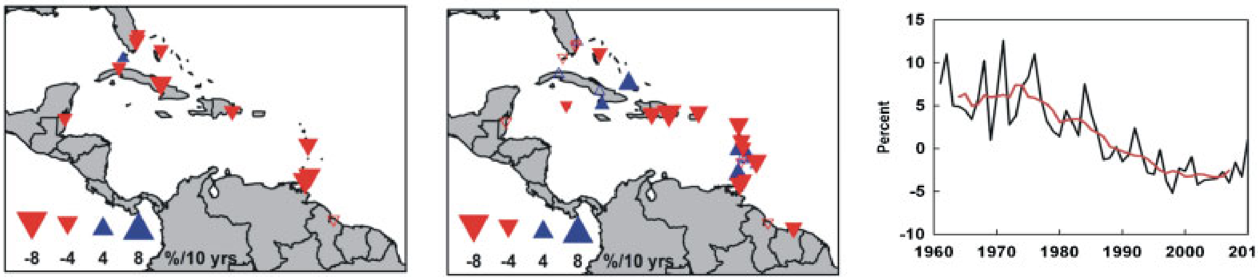


Figure 4. Same as Figure 3 but for the trends in (a) TX90p, (b) TX10p, (c) TN90p and (d) TN10p. Red colour indicates warming, blue indicates cooling trends.

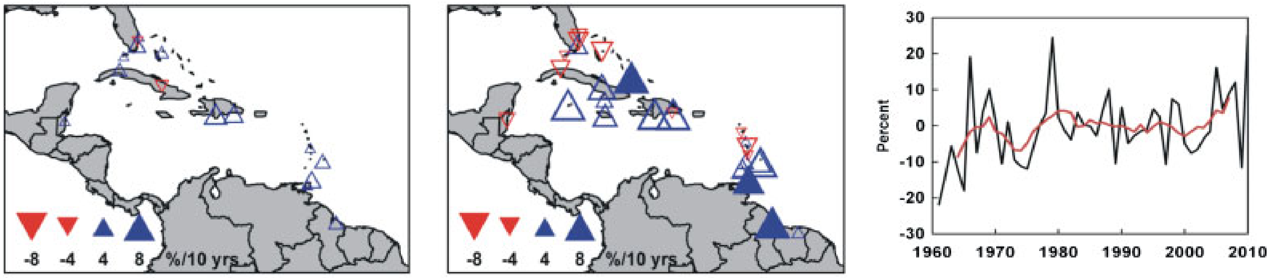
3, respectively. CDD and CWD appear to have been increasing over the past 25 years, though the only CDD significant change was observed in region 1 with an increase of 2.79 days decade^{-1} over the past 25 years.

4.4. Precipitation extremes

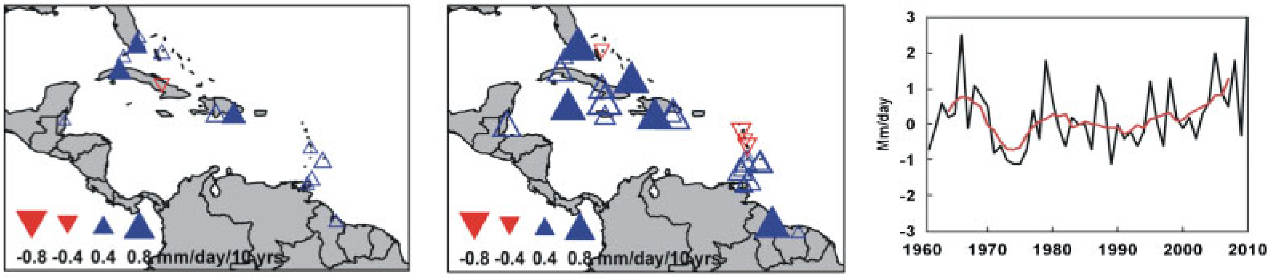
Overall, the results do not show statistically significant change in the frequency of days with precipitation above 10 (R10mm), 20 (R20mm) and 50 (R50mm) mm for 1961–2010 (Table 3 and Figure 6). Likewise, changes in the annual highest daily precipitation (RX1day) and annual highest 5 consecutive daily precipitation (RX5day) were not significant at most stations. Furthermore, only one station, Casablanca (Cuba), noted a significant trend – a rise – in heavy rainfall events (R95p) whereas the rest of the stations suggest a mixed pattern of non-significant small positive and negative trends over the past 50 years.

Similar to the results in precipitation total and intensity, the trends in extreme precipitation are locally more pronounced over the shorter period 1986–2010. Fewer R10mm, R20mm and R50mm were found at most stations in Florida, Bahamas and Cuba whereas the stations in the remaining region indicate more R10mm,

(a) PRCPTOT



(b) SDII



(c) CDD

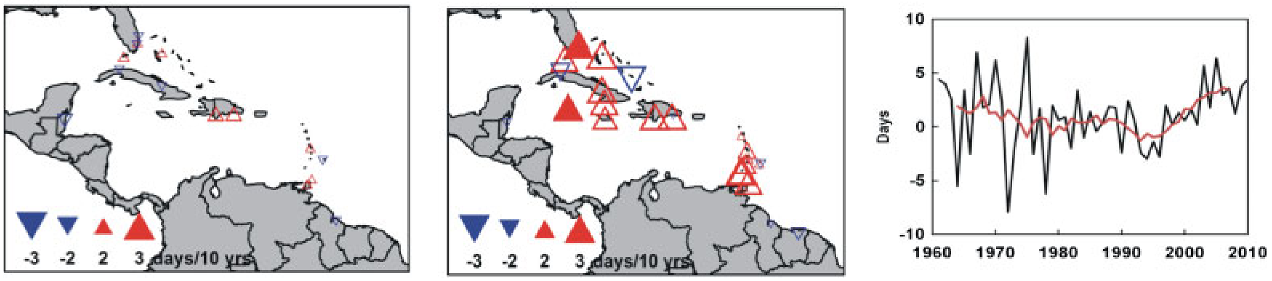


Figure 5. Same as Figure 3 but for the trends in (a) PRCPTOT, (b) SDII and (c) CDD. Blue colour indicates trends toward wetter conditions and red indicates drying trends in (a) and (b). Red colour in (c) indicates trends toward a longer drying spell.

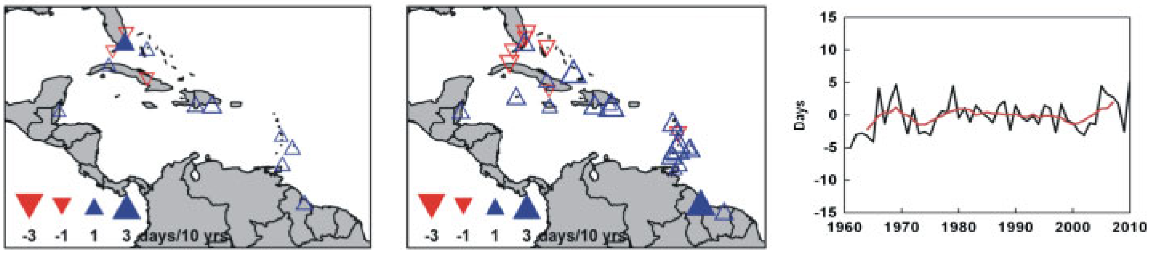
R20mm and R50mm although the majority of the trends are non-significant (Figure 6). A mixed pattern of small positive and negative trends are observed in RX1day (not shown) and RX5day (Figure 6) over the past 25 years. The most significant change is found in the heavy rainfall events (R95p), which are generally rising. This index represents the precipitation due to events above the 95th percentile. A significant R95p increase of 2.93, 4.93 and 2.07% per decade is observed in regions 1, 2 and 5, whereas a significant increase of 2.05% per decade is found in the regional average series for the entire Caribbean region during the past 25 years (Table 3).

5. Discussion

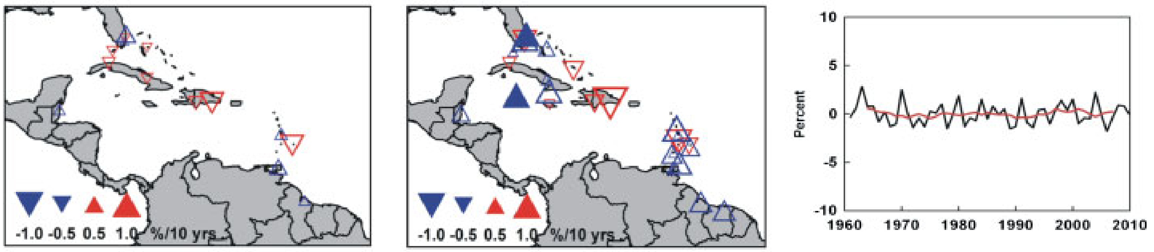
The results presented in this study corroborate previous findings on changes in daily and extreme temperature and precipitation indices across the Caribbean, from local to regional scale. This study suggests trends towards fewer cool extremes and more warm extremes in the Caribbean region during the past 50 years. Similar results were found for neighbouring regions and comparable periods in the analyses of changes in temperature and precipitation extremes in North America (Peterson *et al.*, 2008) and in Central America and northern South America (Aguilar *et al.*, 2005; Skansi *et al.*, 2012) as well as at the country level (see for example Perez *et al.*, 2009 analyses for Cuba). Given the increase in the number of climate records and of the time span covered by them, results on temperature indices are also consistent with those obtained from the previous workshop in the Caribbean region (Peterson *et al.*, 2002) and reanalyses undertaken by Stephenson *et al.* (2008).

Regarding the precipitation indices, this study suggests that although no significant increases were found in the annual total precipitation amount, the intensity of daily rainfall and the heavy rainfall events has been significantly rising over the past 25 years. These results are in agreement with those presented in Peterson *et al.* (2008); Aguilar *et al.* (2005) and Peterson *et al.* (2002). However, it is necessary to mention that the maximum number of CDD, a measure of dry conditions, has been reported as declining in the results of the previous Caribbean workshop (Peterson *et al.*, 2002), whereas this

(a) R20mm



(b) RX5day



(c) R95p

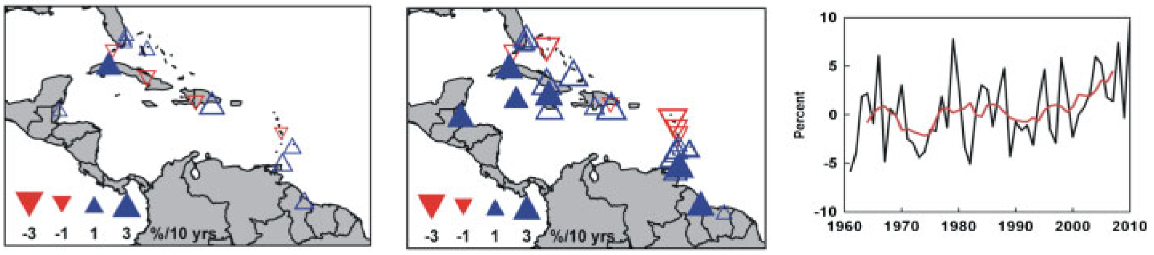


Figure 6. Same as Figure 3 but for the trends in (a) R20mm, (b) RX5day and (c) R95p. Blue colour indicates trends toward wetter conditions and red indicates drying trends.

study suggests an increase in CDD. The regional average series indeed indicates a small but steady decrease in CDD from the 1960s to the mid 1990s (Figure 5) which generally represents the period analysed by Peterson *et al.* (2002). Subsequent to the mid 1990s CDD has trended upwards through to 2010. This explains the CDD positive trends observed in this study, particularly for 1986–2010 and highlights the importance of on-going climate monitoring activities.

The results from the subregional analyses have justified the approach taken in this study – that of examining subregional manifestations of climate extremes. Among the particularly interesting results are the significant positive trends in SDII in regions 1, 2 and 3; the significant positive trend in CDD in region 1; the significant positive trends in R95p in regions 1, 2 and 5 and notably for Cuba. The suggestion for these regions is that more intense rainfall has been recorded over the last 50/25 years interrupted by longer dry spells. This may indicate an increased risk of floods though other factors such as land use and human settlement in flood plains become important as well.

In terms of attributing the observed trends in the temperature and precipitation indices, sea surface temperature (SST) is often invoked as a driving factor. Robust relationships were presented in previous literature, particularly for seasonal rainfall and SST anomalies related to the Atlantic warm pool, tropical/equatorial Atlantic, equatorial Pacific and Pacific–Atlantic gradients (Taylor *et al.*, 2002; Gimeno *et al.*, 2011). Here, a preliminary analysis is undertaken prompted by an apparent shift towards a positive trend for a number of regional average series (for example SDII, CDD and R95p) subsequent to the 1980s. This shift occurs around the same time the AMO transitions into a positive phase. The AMO is a north Atlantic SST signal that influences decadal scale variability in Caribbean precipitation (Enfield *et al.*, 2001; IPCC, 2007). In its positive (negative) phase, the AMO preconditions the Caribbean for wetter (drier) than normal conditions.

As a preliminary analysis, the time series of each index at each individual station was correlated with the AMO annual index (derived from monthly AMO values obtained from the Earth System Laboratory website at http://www.esrl.noaa.gov/psd/data/climateindices/list/). The results indicate that temperature indices are strongly correlated with the AMO index (Figure 7). The correlation for the precipitation indices is weaker but it is still significant at a number of stations. Correlation coefficients calculated between the regional average series and

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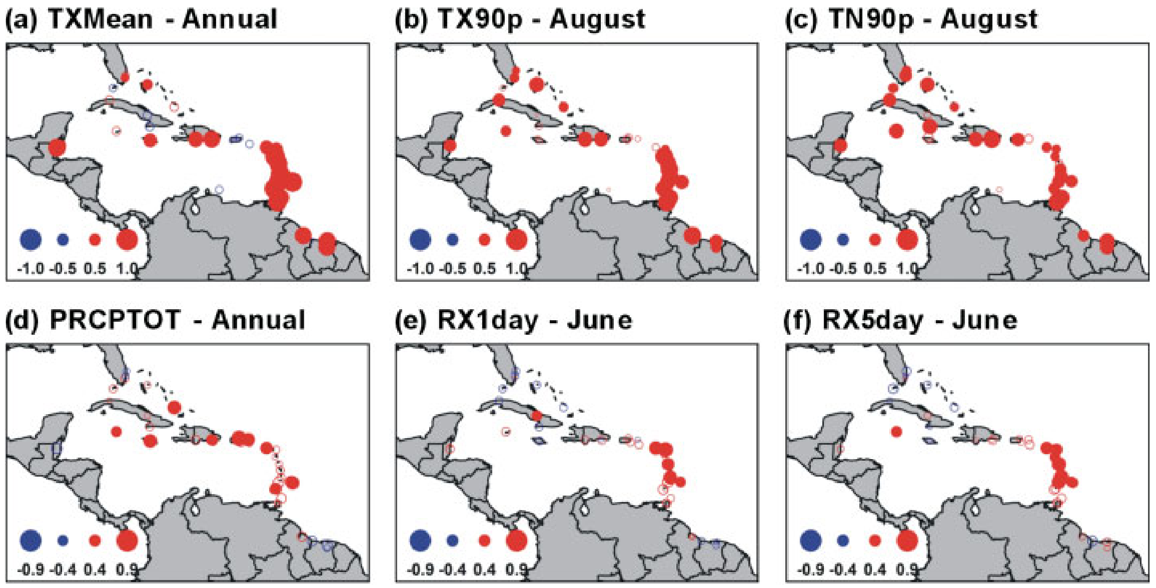

Figure 7. Correlation between the AMO annual (monthly) index and (a) annual TXmean, (b) August TX90p, (c) August TN90p, (d) annual PRCPTOT, (e) June RX1day and (f) June RX5day. Significant correlation ($p \leq 0.05$) is indicated by a full circle.

Table 4. Correlation coefficient calculated between annual temperature and precipitation indices regional series for 1961–2010 and the AMO annual index.

Element	Index	Correlation
Temperature	TXmean	**0.62**
	TNmean	**0.64**
	DTR	**−0.36**
	TX90P	**0.86**
	TX10P	**−0.50**
	TN90P	**0.80**
	TN10P	**−0.64**
	TXx	**0.73**
	TXn	0.13
	TNx	**0.70**
	TNn	**0.34**
Precipitation	PRCPTOT	**0.37**
	SDII	**0.63**
	CDD	0.19
	CWD	0.14
	R10mm	**0.28**
	R20mm	**0.32**
	R50mm	**0.41**
	RX1day	0.19
	RX5day	0.15
	R95p	**0.52**

Bold values correspond to correlation significant at the 5% level.

the AMO (presented in Table 4) reveal significant correlations for all temperature indices (with the exception of TXn) and most precipitation indices (PRCPTOT, SDII, R10mm, R20mm, R50 mm and R95p).

As all temperature indices and two precipitation indices (RX1day and RX5day) are also provided on a monthly basis (Table 2), the monthly time series at each station was correlated with the corresponding month's AMO index. The results indicate that, for the temperature indices, stations show significant correlation with the AMO monthly index and correlations are strongest in August and September (Figure 7). This suggests that the AMO signal is more pronounced on temperature during the end of the summer than for other periods of the year. For the precipitation indices RX1day and RX5day, stations display significant correlation with the AMO monthly index and correlations are strongest in June and October (corresponding to the early and late rainfall seasons). Figure 7 also shows that most of the stations with significant correlation are located in region 4. These results further suggest that there is an Atlantic SST signal in the variability of the temperature and precipitation extreme events and there is a need for further investigation and detailed attribution studies.

6. Summary and conclusion

This study presents the trends in indices of temperature and precipitation in the Caribbean region and adjacent countries for 1961–2010 and 1986–2010. Data were carefully examined for quality and homogeneity by local experts and a consistent methodology was applied for the preparation and analysis of the indices. This study presents the results of the second workshop on climate change indices which was held to further explore the trends in extreme precipitation and temperature indices with more data than available during the workshop in 2001. The resulting manuscript was designed to offer a more detailed spatial representation of the changes in extremes for the Caribbean region than presented in previous studies.

Overall, the land stations show a significant warming of the surface air temperature along with the nighttime temperature increasing more than the daytime temperature. The frequency of warm days, warm nights and extreme high temperatures has increased while fewer cool days, cools nights and extreme low temperatures were observed. Changes in precipitation indices were less consistent. Small increasing trends were found in annual total precipitation, daily intensity, maximum number of CDD and heavy rainfall events particularly during the period 1986–2010.

Recent climate change in the Caribbean region is observed in rising temperature along with trends towards more warm extremes, less cold extremes as well as strong indications for enhanced heavy precipitation, not only region-wide, but also in different geographic sectors. The decadal variability in temperature and, to a lesser extent, rainfall extremes, is related to the AMO signal of the North Atlantic SSTs.

A next step to this study involves a detailed assessment of climate extreme indices from global and regional model scale output in order to assess model skill in representing present day extremes, and to analyze future projections for the near term and end of century (see for example Hall *et al.*, 2012). This information would be particularly useful to the Caribbean for the purposes of managing disaster risks and adaptation planning.

The issue of historic data rescue in support of climate change analyses is an important one for the Caribbean. Data collection in the Caribbean context involves data obtained from a network of meteorological stations maintained by national meteorological services, supplemented by stations either owned by other government entities, or that are privately owned particularly those on farms and estates. National weather services are often challenged with inappropriate storage and archiving of historical observational records, with some data still on deteriorating paper or as electronic data scattered across many agencies. One of the aims of the workshop was to highlight this and point to recent data rescue initiatives such as incorporated in the Caribbean Agrometeorological Initiative (CAMI) project executed by the Caribbean Institute for Meteorology and Hydrology (CIMH) or the Camaguey (Cuba) historic observations that are being hand digitized. Indeed countries welcome such initiatives and partnerships that will assist recovery of historic data, as in the case of Jamaica where archived historic microfilm weather data are yet to be digitized. The workshop facilitated the discussion of technologies that facilitate digitization and highlighted regional institutions, e.g. CIMH, or international institutions, e.g. the International Environmental Data Rescue Organization (IEDRO), that can assist such activities. The CIMH is already undertaking a larger data rescue project that incorporates all 16 member states of the Caribbean Meteorological Organization in comparison to the 10 countries covered in the CAMI project and will possibly serve as the hub for similar coordinated activities. The project is also developing a centralized database system with interactive portal to better facilitate data sharing and dissemination.

The workshop held at the University of the West Indies in Jamaica has provided a great opportunity not only to improve our understanding of changes in climate extremes but also to establish a strong scientific network for scientists working on climate change and historical data rescue in this region. This study represents an important contribution to climate change research. The indices will be made available to the international research community on the ETCCDI website at http://etccdi.pacificclimate.org/data.shtml.

Acknowledgements

The capacity building workshop on data rescue and climate change indices held in Kingston, Jamaica on May 7–10 was supported by the World Meteorological Organization, the National Oceanic and Atmospheric Administration and the Caribbean Community Climate Change Centre. The participants greatly enjoyed the hospitality provided by the Department of Physics at the University of the West Indies, Mona. Data compiled from *The Caribbean Agrometeorological Initiative* (*CAMI*) project executed by the Caribbean Institute for Meteorology and Hydrology and supported by the European Union funded African Caribbean and Pacific Group of Countries (ACP) Science and Technology Programme complemented the data provided by meteorological services across the Caribbean, Guyana and Belize. Special thanks to Shontelle Stoute and Lisa Kirton-Reed for their contribution to the CAMI Project. Other data were obtained from the National Climatic Data Centre online archive and from Météo-France. Special thanks to the directors of the National Meteorological and Hydrological Services for facilitating the participation of their staff in the workshop and for providing data.

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