ORIGINAL PAPER

# Variations in extreme temperature and precipitation for a Caribbean island: Trinidad

Sharlene Lata Beharry · Ricardo Marcus Clarke · Kishan Kumarsingh

**Abstract** Temperature and precipitation in situ datasets for the Caribbean island, Trinidad for 1961–2010 were statistically analyzed using the RClimDex software and the Mann-Kendall test for trends. The annual, seasonal, and monthly findings were compared with regional projections; Providing Regional Climates for Impact Studies (PRECIS) and a 20 km atmospheric global circulation model, and a global projection of the Coupled Model Intercomparison Project Phase 3 (CMIP3). Overall, the seasonal and decadal results revealed patterns different from the annual warming. All the temperature indices were found to have warming patterns with the wet season, June to December, generally greater than the dry season, January to May. The warmest decade was 1980s, whereas globally, the decade 2001–2010 was the warmest. There was an increase in the annual maximum 5 day precipitation, RX5day, at the UWI station. During the dry season (1973–2010) at the UFS and UWI stations, the RX5day increased by 8.60 and 7.76 mm per decade, respectively, while the maximum 1-day precipitation, RX1day, increased by 2.92 and 8.90 mm per decade for the UFS and UWI, respectively. The 1980s was the wettest, and during the decade 2001–2010, there were above averages for the consecutive dry days (CDD) and the simple daily intensity index (SDII). The projections on both the regional and global outlooks suggest that this warming pattern will continue in the future. This small-scale study supports that seasonal and decadal analyses, in addition to the annual assessments, are significant for the understanding of the climate variability which is required for vulnerability and adaptation studies for small island states.

## 1 Introduction/Objectives

The risks associated with extreme climate events and our ability to assess and manage them affect the sustainability of economic development and living conditions. It was projected that some extremes will become more frequent, widespread, and intense during the 21st century (IPCC 2007). These may lead to more droughts or flooding events and may affect water resources, agriculture, infrastructure, and biodiversity. Current information on changes in climate extremes is therefore needed to aid in vulnerability assessments and mitigation options. Recent trends in both temperature and precipitation and their related extreme indices are supported by studies on the global and regional scales which clearly show a tendency of a warming climate (Trenberth et al. 2007; Karmalkar et al. 2013 and Stephenson et al. 2014). The IPCC 5th Assessment Report stated that almost the entire globe has experienced surface warming, and the global mean surface air temperature rose at a rate of 0.85 °C over the period from 1880 to 2012 (IPCC 2013). Over small island states such as in the Caribbean, Indian Ocean, and Mediterranean regions, analyses show warming ranged from 0 to 0.5 °C per decade for the 1971 to 2004 period (Trenberth et al. 2007). Furthermore, there is a good agreement with the historical temperature trends for the Caribbean and the global warming patterns (Karmalkar et al. 2013 and Stephenson et al. 2014).

A global analysis of extreme weather was coordinated by efforts by the joint World Meteorological Organization Commission for Climatology (CCI)/World Climate Research

S. L. Beharry (✉) · R. M. Clarke
The Environmental Physics Laboratory, Department of Physics, The University of the West Indies, St Augustine, Trinidad and Tobago
e-mail: sharlenelata@yahoo.com

R. M. Clarke
e-mail: ricardo.clarke@sta.uwi.edu

K. Kumarsingh
Multilateral Environmental Agreements Unit,
The Republic of Trinidad and Tobago, Ministry of Environment and Water Resources, Port of Spain, Trinidad and Tobago
e-mail: anamika_tt@yahoo.com

Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) (ETCCDMI 2009). The main outcome from this international coordination was a suite of 27 climate change indices, derived from daily temperature and precipitation data which primarily focuses on extreme events. These extreme climate indices and a user-friendly software package written in R (RClimDex) are freely available to the international research community (ETCCDMI 2009). Another effort by the ETCCDMI was the coordination of regional workshops with the aim of addressing the gaps and availability of data and thereafter analyzing the trends of the extreme climatic indices for a particular region. As a result of these workshops, regional analyses were done for the Caribbean region (Peterson et al. 2002 and Stephenson et al. 2014), initially for various countries in Africa (Easterling et al. 2003) and later focusing on the southern and west Africa (New et al. 2006), also for the Middle East (Zhang et al. 2005; Sensoy et al. 2007), the South American continent (Vincent 2005; Haylock et al. 2006), for the central and northern regions of South America (Aguilar et al. 2005), and for central and south Asia (Peterson 2005; Klein Tank et al. 2006). Recognizing the successes and findings of these workshops, other in-depth studies were done using the RClimDex software to assess trends in daily climate extremes in precipitation, temperature, and, in some cases, both; over Brazil (Dufek and Ambrizzi 2008), in the Hawaiian Islands (Chu et al. 2010), in South America (Skansi et al. 2013), Utah, USA (Santos, Carlos Antonio Costa dos 2011), for Pakistan (Abbas et al. 2013), and the northwestern region of China (Wang et al. 2013). Likewise, a global approach was taken by Alexander et al. (2006) and more recently by Donat et al. (2013).

The Caribbean region is vulnerable to temperature and precipitation variability. For example, warming may increase the frequency of vector-borne diseases, cause changes or even loss of species in biodiversity, and heighten coral bleaching. Changes in rainfall patterns possibly will alter the availability of fresh water and lead to a higher frequency of droughts and flooding events. A higher frequency in heavy rainfall events in the Caribbean region may result in the increased probability of flooding. It is therefore evident that assessments of the climatic parameters are necessary. These analyses will not only add to the understanding of the climatology but will also be useful for policy makers so that strategies can be developed to mitigate extreme climate-induced events.

For the Caribbean region, using daily weather observations with datasets of varying lengths for the interval 1958–1999 and climate indices from ETCCDMI, it was reported that area average percentage of days having very warm, maximum, and minimum temperatures has increased considerably since the 1950s, while the frequency of days with cold temperatures has decreased (Peterson et al. 2002). In addition, there was a

decrease in the maximum number of consecutive dry days (CDD).

A second Caribbean climate change workshop (Stephenson et al. 2014) extended the 1958–1999 dataset analyzed by Peterson et al. (2002) to 2010, simultaneously included more meteorological datasets and presented the results based on six subregions. The number of regions used included two newly defined regions which were based on the most recent classification by Jury and Winter (Jury et al. 2007). Results of Stephenson et al. (2014) generally agreed with those of Peterson et al. (2002) with the exception that the CDD which was previously reported as having a decreasing trend now appears to be increasing. Another study, Neelin et al. (2006) found that the June, July, and August recorded rainfall amounts have decreased in the last few decades. The classification of the Caribbean regions is essential to the analysis of the trends of the climate on a subregional and local scale.

Surface air temperatures, precipitation, and extreme events are key indicators that provide scientific evidence for variation and change in the climate. Decadal and multi-decadal analyses of climate parameters give a more robust approach to assessing and monitoring climate variability extremes and change, since such is not possible with annual climate monitoring (WMO World Meteorological Organization (WMO) 2013). Peterson et al. (2002) strongly suggested and supported that extreme indices are dominated by variability on the annual to decadal scales and that linear trend alone does not do a good job of representing the observed changes. WMO assessed the global temperature and precipitation using a decadal approach and found that in the decade 2001–2010 unprecedented high impact climate extremes were experienced, varying from being the wettest since 1901 and the warmest for the northern and southern hemispheres for both land and ocean surface temperatures (World Meteorological Organization (WMO) 2013).

For the Caribbean, two significant recent regional studies (Peterson et al. 2002 and Stephenson et al. 2014) highlighted local and regional findings of the region's annual precipitation and temperature indices. Regional studies may mask significant impactful variations at the smaller spatial scale therefore, it is also useful to carry out local studies. Beharry et al. (2013) built on past analyses of Trinidad's precipitation, Wehekind and Smith (1955), Garstang (1959), Seepersad (1977), Singh (1997) and Stone (2001), by utilizing daily data for the period 1959-2010 and assessing the average rainfall seaonal variation and the trends using a nonparametric approach. It was noted that local studies on Trinidad's temperature are sparse with Granger (1982), Singh (1997), and Stone (2008) among the few investigators, thus highlighting a need for an appropriate robust analysis for a signal of climate variation, inclusive of analyses of maximum and minimum temperatures and their extreme events. The main objectives of

our study therefore are to perform further analyses of Trinidad's, the southernmost small island in the Caribbean, temperature and precipitation indices on the seasonal and decadal scales and to compare with the regional studies and climate model outputs. These climate models include a regional model, Providing Regional Climates for Impact Studies (PRECIS), the global projections by the Coupled Model Intercomparison Project Phase 3 (CMIP3), and a 20-km atmospheric global circulation model. We have also included one more precipitation station compared with those used by Stephenson et al. (2014).

## 2 Study area

Trinidad and Tobago, the southernmost state in the tropical Caribbean chain, is located off the north eastern point of Venezuela. According to the Meteorological Services of Trinidad and Tobago (MET), there exist two seasonal climates for Trinidad which are the tropical maritime and modified moist equatorial (Trinidad and Tobago Meteorological Services 2009). The tropical maritime is characterized by warm days and cool nights in the dry season during the months of January to May. The heating from the day results in convectional rainfall during nights. Hot humid days and nights are generally observed during the wet season, June to December, influenced by the modified moist equatorial climate. The dry season has a lower recorded rainfall monthly average of 63.5 mm compared with the wet season monthly average of 217.5 mm. Using in situ daily data for the period 1961–2010, the seasonal variation between the maximum daytime and minimum nighttime temperatures was determined to be 0.9 °C with the average daily difference between the daytime and nighttime temperatures being slightly greater during the dry season (9.2 °C) than in the wet season (8.3 °C) (Beharry 2012). The average maximum and minimum temperatures were 31.4 and 22.7 °C, respectively. The hottest months were found to be May, September, and October while the coldest months were January and December (Beharry 2012).

Trinidad is 4862 km² (Trinidad and Tobago, Water Resouces Agency (WRA) 2001) and is surrounded by different seas; to the north the Caribbean Sea, to the east the North Atlantic Ocean, to the south the Columbus Sea, and the Gulf of Paria on the west. The topography of Trinidad is characterized by five physiographical regions. From the North to the South, these are the Northern Range, the Northern Basin, the Central Range, the Southern Basin, and the Southern Range. The Northern Range runs from the east to the west and has the two highest peaks, El Cerro del Aripo and El Tucuche, with heights of 940 and 936 m (Trinidad and Tobago. Central Statistical Office (CSO) 2012), respectively. The Central and Southern Ranges (300 m) are lower than the Northern Range.

The Northern Basin has flat lands, namely the Caroni Basin and the Caroni Swamp. The Narvia Swamp bounds the Southern Basin to the east of the Central Range, and west of the Southern Basin is the Oropouche Lagoon.

### 2.1 Data

Due to the unavailability of data, only the northern region of the island of Trinidad was represented by station data. In the Caribbean region, continuous daily time series with metadata is a challenge (Peterson et al. 2002) together with the ability to convert and maintain the climatological data digitally (Stephenson et al. 2014), and Trinidad is a case in point. Data used in this study was accessed from the Trinidad and Tobago Meteorological Services, Piarco situated at the International airport, and the University of the West Indies, St. Augustine. These datasets included the daily maximum and minimum temperatures for The University of the West Indies Field Station (UFS) and Piarco Meteorological Services (Piarco) and daily precipitation data for Piarco, the UFS, and The University of the West Indies, St Augustine (UWI). The details of geographical locations of the stations, time periods, and number of years of data are given in Table 1. The geographical coordinates and locations of the stations are shown in Fig. 1.

## 3 Data quality control, trend tests, and climate indices

This section presents the related climate indices, data quality control measures and the methods used for assessment of the trends in the precipitation and temperature datasets. The RClimDex is an upgraded version of the ClimDex climate indices which was used to assess and detect evidence of a climatic variability presenting the results as annual linear trends. RClimDex has been used by many including Klein Tank et al. (2006), Alexander et al. (2006), dos Santos et al. (2011), Fan et al. (2012), Insaf et al. (2013), and Stephenson et al. (2014).

Measures were taken to ensure the high quality of data of the daily maximum temperatures (TX), minimum temperatures (TN), and precipitation. In the examination of the datasets for missing data, there were no missing data in the Piarco precipitation, the UWI precipitation, and UFS temperatures time series; however, for the UFS precipitation dataset, 30 consecutive days in June 1980 were missing due records being lost in a fire and for Piarco temperatures; during the years 1961 and 1962, there were gaps in the time series, in which more than 3 consecutive days of data were missing. In 1 month, if 3 consecutive daily data were missing, it is recommended that the month be omitted (WMO 1989). We adopted and applied this condition to our assessment; therefore, as a result, the temperature dataset used for Piarco was

**Table 1** Temperature and precipitation stations with geographical locations, time period for data, and the number of years

| Station name | Latitude north | Longitude west | Time period (no. of years) | Source |
|---|---|---|---|---|
| Piarco[a, b] | 10° 35′ 14″ | 61°20′37″ | 1959–2010 (52) | Trinidad and Tobago Meteorological Office |
| University of the West Indies (UWI)[b] | 10° 38′ 13″ | 61°23′59″ | 1987–2010 (24) | The University of the West Indies, St Augustine |
| U.W.I Field Station (UFS)[a, b] | 10° 38′ 50″ | 61°25′50″ | 1973–2010 (38) | |

[a] Represents daily temperature datasets

[b] Represents daily precipitation datasets

from 1963 to 2010. It must be noted that there were 14 missing days spread across the remaining time series (1963–2010) which were replaced using the estimation method. Due to the limited data, the method of estimation was an average of the remaining recorded values.

The precipitation and temperature time series were also checked for negative values. Temperatures below 0 °C are not experienced in tropical regions such as Trinidad, and negative precipitation values are unrealistic; therefore, these values may have been as a result of erroneous data entry. Furthermore, the pairs of maximum and minimum temperatures were examined for values which were outside four standard deviations of the climatological mean of the value of the day and values of TN greater than TX. For these additional examinations, the following were noted: there were no negative values, TNvalues were all less than TX, and there were no values outside the four deviations in the datasets.

Nonetheless, in the event of the detection of any of these instances of erroneous data, the value would have been considered missing, and an estimate would replace the value or otherwise assign a default value.

The homogeneity of the datasets was assessed using the RH test version 4 package to detect multiple change points (shifts) which may have existed in the data series. These were detected, recorded, and the time series adjusted. The RH test included the penalized maximal $t$ test (Wang et al. 2007) and the penalized maximal $F$ test (Wang 2008). The RClimDex package also considered the lag-1 autocorrelation (ETCCDMI 2013) which was also applied in our study.

The temperature and precipitation indices selected for this study are listed in Table 2. The ten temperature indices are the annual mean maximum temperature (TXmean), the annual mean minimum temperature (TNmean), the monthly
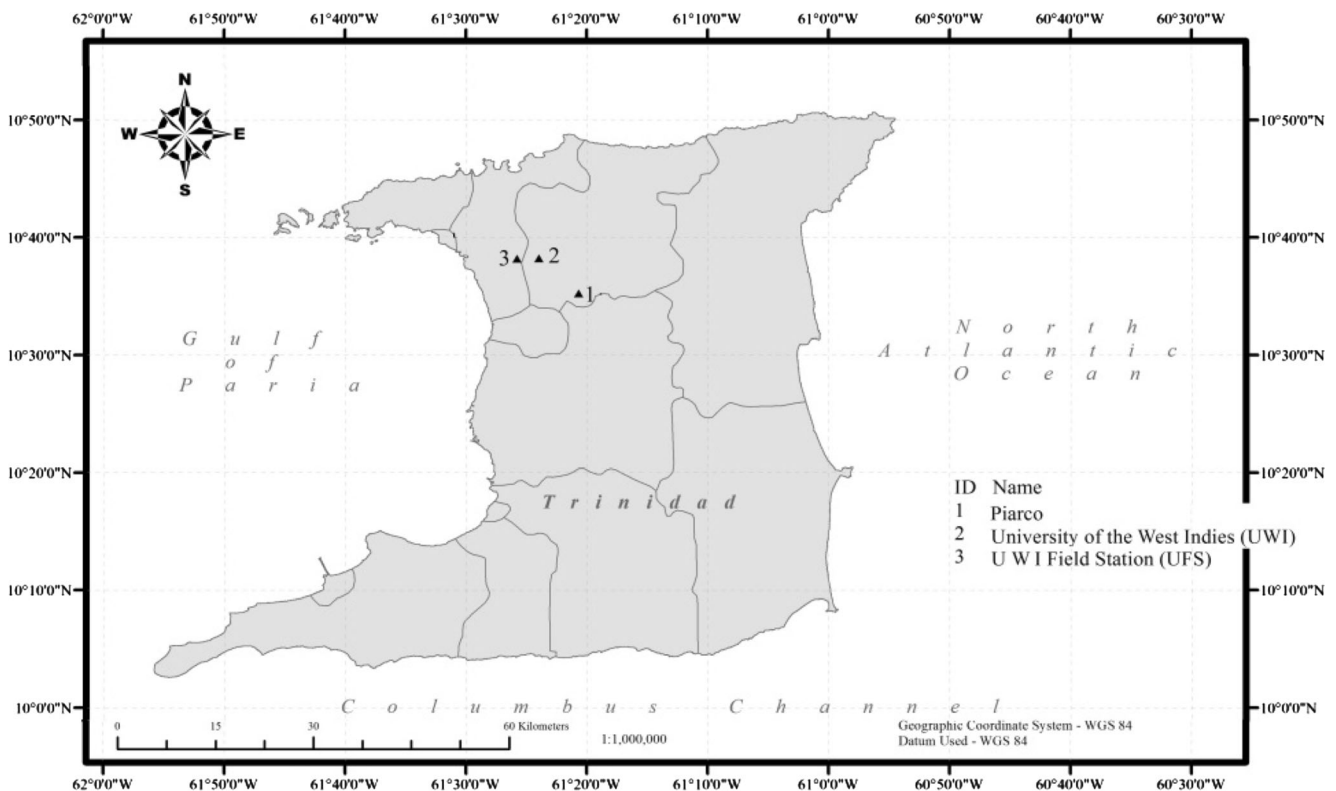


**Fig. 1** Geographical locations of Piarco, UWI, and UFS

**Table 2** The extreme temperature and precipitation indices ID, name, the definitions, and associated units where TX is the maximum temperature and TN is the minimum temperature

| | ID | Index name | Indices definitions | Units |
|---|---|---|---|---|
| Temperature | TXmean | Annual maximum temperature | Annual mean of the daily maximum temperature | °C |
| | TNmean | Annual minimum temperature | Annual mean of the daily minimum temperature | °C |
| | $TX_x$ | Highest TX | Monthly maximum value of daily maximum temperature | °C |
| | $TX_n$ | Lowest TX | Monthly minimum value of daily maximum temperature | °C |
| | $TN_x$ | Highest TN | Monthly maximum value of daily minimum temperature | °C |
| | $TN_n$ | Lowest TN | Monthly minimum value of daily minimum temperature | °C |
| | TN10p | Cool nights | Percentage of days when TN<10th percentile | % days |
| | TX10p | Cool days | Percentage of days when TX<10th percentile | % days |
| | TN90p | Warm nights | Percentage of days when TN>90th percentile | % days |
| | TX90p | Warm days | Percentage of days when TX>90th percentile | % days |
| Precipitation | PRCPTOT | Annual total wet day precipitation | Annual total rainfall from wet days rainfall >1 mm | mm |
| | R95p | Very wet days | Annual total precipitation when the RR >95th percentile from the period reference period * | mm |
| | R99p | Extremely wet days | Annual total PRCP when RR>99th percentile | mm |
| | RX1day | The highest 1-day rainfall amount | Annual maximum 1-day precipitation | mm |
| | RX5day | The highest 5-day rainfall amount | Annual maximum consecutive 5-day precipitation | mm |
| | SDII | Simple daily rainfall intensity index | Annual total precipitation divided by the number of wet days (defined as precipitation≥1.0 mm) in the year | mm/day |
| | R10 mm | Number of heavy precipitation days | Annual count of days when daily rainfall >10 mm | days |
| | R20 mm | Number of very heavy precipitation days | Annual count of days when daily rainfall >20 mm | days |
| | CWD | Consecutive wet days | Maximum number of consecutive days with daily rainfall≥1 mm | days |
| | CDD | Consecutive dry days | Maximum number of consecutive days with daily rainfall>1 mm | days |

The reference period for the three stations varied, for Piarco 1961–1990, for UFS 1981–2010, and for UWI 1991-2010

maximum value of the daily maximum temperature (TXx), the monthly minimum value of the daily maximum temperature (TXn), the monthly maximum value of the daily minimum temperature (TNx), the monthly minimum value of the daily minimum temperature (TNn), the percentage of days when TX is less than the 10th percentile (TX10p) referred as cool days, the percentage of days when TX is greater than the 90th percentile (TX90p) referred as warm days, the percentage of days when TN is less than the 10th percentile, and cool nights (TN10p) and the percentage of days when TN is greater than the 90th percentile, warm nights (TN90p). The ten relevant precipitation indices included in our analysis are the annual total rainfall from wet days with rainfall greater than 1 mm (PRCPTOT), very wet days (R95p), extremely wet days (R99p), the highest 1-day rainfall amount (RX1day), the highest 5-day rainfall amount (RX5day), the number of heavy precipitation days (R10mm), the number of very heavy precipitation days (R20mm), the number of consecutive wet days (CWD), the number of consecutive dry days (CDD), and the simple daily rainfall index (SDII).

The temperature extreme climate indices were based on a threshold value established on a 30-year period, 1971–2000, while the precipitation reference periods for the three stations were different, because of the varying lengths of the datasets.

These precipitation reference periods were 1961–1990 for Piarco, 1981–2010 for UFS, and 1991–2010 for UWI. For the reference period, the corresponding 5th percentile was used as the threshold value for the lower threshold, while the 95th percentile for the upper threshold. These values were used as inputs in the RClimDex analyses.

The RClimDex software included a component to determine the linear trends which were calculated using the least square regression. The trend was significant at the 95 % level of confidence if the $p$ value was less than 0.05. The software calculated the annual and monthly trends; therefore, for the seasonal assessment, the Mann-Kendall test (Mann 1945) was used to determine if monotonic trends were present while the Sen's Estimator (Sen 1968) was applied to estimate the value of the linear trend. The Mann-Kendall test and the Sen's Estimator combination have been used successfully in climate studies by Hamed (2008), Tabari and Talaee (2011), Tabari and Hosseinzadeh Talaee (2011) and Gocic and Trajkovic (2013). This combination of the Mann-Kendall and Sen's estimator was applied to the annual, seasonal and decadal indices. The seasonal indices were defined by a dry season, January to May and a wet season, June to December. Considering the annual indices, the results of the Mann-Kendall trend tests and those of the RClimDex were compared and found to be alike.

## 4 Results

### 4.1 Maximum and minimum temperatures

The annual means of the daily maximum and minimum temperatures, TXmean and TNmean, for the period from 1963 to 2010 have indicated a general warming. TXmean showed an annual warming at the rate of 0.41 °C per decade for Piarco and 0.33 °C per decade for UFS, while for TNmean, the corresponding rates were 0.40 and 0.46 °C per decade. Although similar warming patterns were observed at both stations, at the UFS, the warming during the night, TNmean, was greater than the warming during the day, TXmean. Seasonally, for Piarco and the UFS, it was noted that the daytime and nighttime warming was greater in the wet season compared with the dry, with the exception of Piarco's nighttime temperatures (Table 3).

The decadal analysis revealed that for both Piarco and the UFS, the decade 2001–2010 was the warmest, with the decades 1981–1990 and 1991–2000 having positive anomalies slightly less than the decade 2001–2010. The warmest year within the decade 2001–2010 was 2010 with 2003, 2004, 2005, and 2008 among the top ten warmest years for the period 1961–2010. Similarly, 2010 was the warmest year for the UFS, with 2003, 2005, 2007, and 2009 falling within the top ten warmest years for the period 1961–2010. In the decade 1971–1980, there were below average anomalies for both stations (Fig. 2).

There appears to be a general increasing trend in TXmean and TNmean, though at the UFS, there was a greater warming than at Piarco (Fig. 3). For 1963 to 2010 at Piarco and for 1972 to 2010 at the UFS, the warmest day (TXx) and the warmest night (TNx) of the year have increased by 0.33 to 0.57 °C per decade (Table 3). Likewise, there were increases in the temperatures of the coolest day (TNx) and coolest night (TNn) of

the year of 0.44 and 0.81 °C per decade (Table 3). The dry and wet seasons showed similar warming trends with the magnitude of the trend generally higher in the wet season (Table 3).

### 4.2 Warm and cool days and warm and cool nights

Analysis of the annual percentage of warm days and nights was done through the TX90p and TN90p indices while for the cool days and nights, TX10p and TN10p, respectively, were used. The warm days represented the maximum temperatures above 31.5 °C for Piarco and UFS, while cool days represented the maximum temperatures below 30.4 °C for Piarco and 30.3 °C for UFS. Minimum temperatures above 23.3 °C for Piarco and 22.4 °C for UFS and below 21.3 and 20.3 °C for Piarco and UFS, respectively, which correspond to the warm and cool nights. At both stations, warm days and nights significantly increased between 1.62 and 6.78 % per decade, whereas the frequency of cool days decreased by 2.94 (Piarco) and 4.49 (UFS)% per decade, and the frequency of cool nights decreased by 4.38 and 5.69 % per decade, for Piarco and the UFS, respectively (Table 3).

The annual frequency of the cool nights showed decreases of 4.38 and 5.69 % of days per decade for Piarco and the UFS, respectively. Similarly, there were decreases in the frequency of cool days by 2.94 (Piarco) and 4.49 % per decade (UFS) (Table 3). For both the dry and wet seasons, the frequencies of the cool days and nights significantly decreased.

The frequencies of cool days and nights by decade have decreased in the decade 2001–2010 by 5.5 and 8.7 % for Piarco (Fig. 4a, c). These were the largest decreases among the five decades examined. On the other hand, there were detected increases of number of TX90p and TN90p at the rate of 19.9 and 20.6 % per decade at Piarco in the decade 2001–2010.

**Table 3** Annual and seasonal trends of the extreme indices of air temperature for Piarco and UFS stations, Trinidad

| Indices | Unit | Piarco (1963–2010) | | | UFS (1972–2010) | | |
|---|---|---|---|---|---|---|---|
| | | Annual | Dry | Wet | Annual | Dry | Wet |
| TX mean | °C per decade | *0.41* | *0.35* | *0.44* | *0.33* | *0.30* | *0.34* |
| TN mean | | *0.40* | *0.42* | *0.38* | *0.46* | *0.46* | *0.48* |
| TXx | | *0.57* | *0.40* | *0.51* | *0.33* | *0.21* | *0.34* |
| TXn | | *0.24* | *0.37* | *0.37* | *0.56* | *0.37* | *0.33* |
| TNx | | *0.33* | *0.30* | *0.34* | *0.43* | *0.33* | *0.38* |
| TNn | | *0.44* | *0.51* | *0.44* | *0.81* | *0.60* | *0.63* |
| TX10P | % of days per decade | *−2.94* | *−2.72* | *−2.69* | *−4.49* | *−3.86* | *−3.69* |
| TX90P | | *5.79* | *3.89* | *5.89* | *4.10* | *1.62* | *5.40* |
| TN10P | | *−4.38* | *−4.21* | *−4.14* | *−5.69* | *−6.29* | *−5.13* |
| TN90P | | *6.41* | *5.48* | *6.39* | *5.86* | *3.89* | *6.78* |

Italicize values represent 95 % significant level ($p < 0.05$)
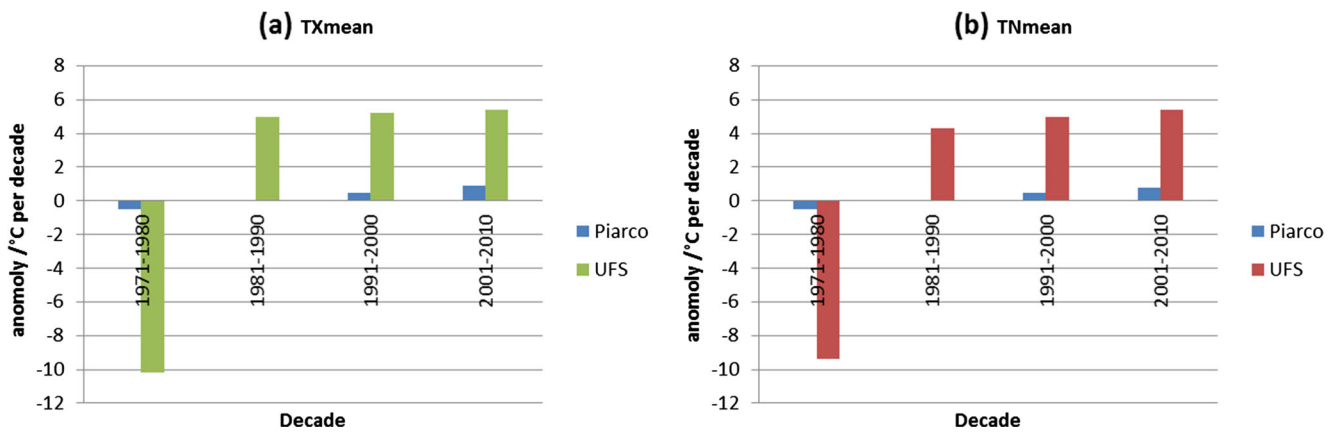
**Fig. 2** The decadal anomalies for the annual maximum temperature (TXmean) and the annual minimum temperature (TNmean) for the period 1971–2010. The UFS decade is actually from 1972–1980

### 4.3 Annual total precipitation

The annual total precipitation index, PRCPTOT is one of the most extensively analyzed indices in climatology in which temporal patterns of rainfall amounts can be observed. No statistical significant monotonic trends were found at the three meteorological stations in Trinidad, in the annual and monthly precipitation (Beharry et al. 2013). Our analyses from a decadal approach (Fig. 5a) of the annual precipitation anomalies

indicated that the decade 1981–1990 was wetter than average. At Piarco, the annual precipitation anomalies showed that in the decade 1981–1990, 7 individual years were above normal with respect to the reference period 1961–1990 while the other 3 years recorded drier than average. The years which were wetter than normal were 1981 which was the wettest year with 2603.2 mm of rainfall recorded, that is a 746.4 mm above normal precipitation, 1982 the 4th wettest year, 1983 the 2nd wettest year, 1984, 1985, 1986, and 1988. Significantly, the
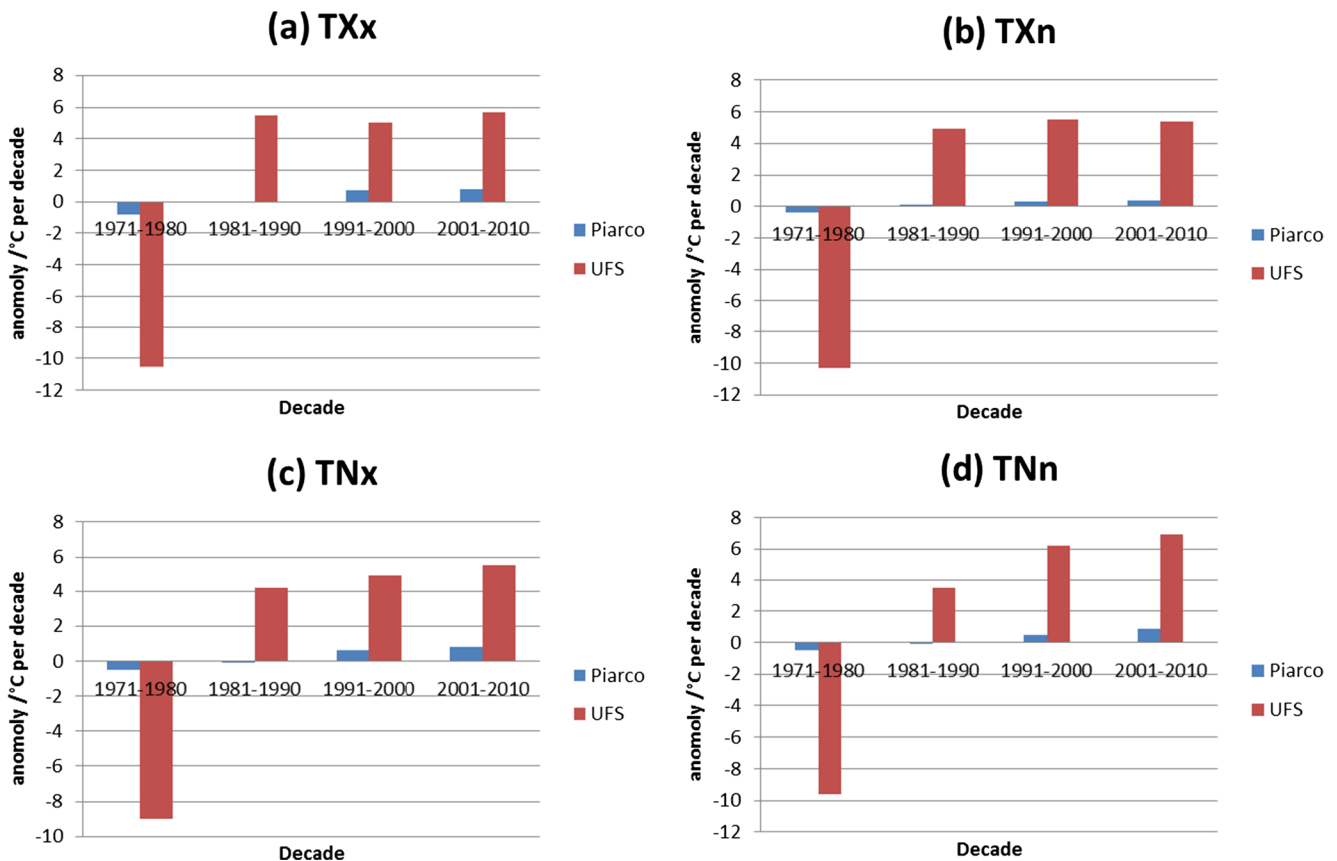


**Fig. 3** The decadal anomalies for the highest maximum temperature (TXx) and lowest maximum temperature (TXn), the highest minimum temperature (TNx), and the lowest minimum temperature (TNn) for the period 1971–2010. Note the UFS decade is actually from 1972–1980
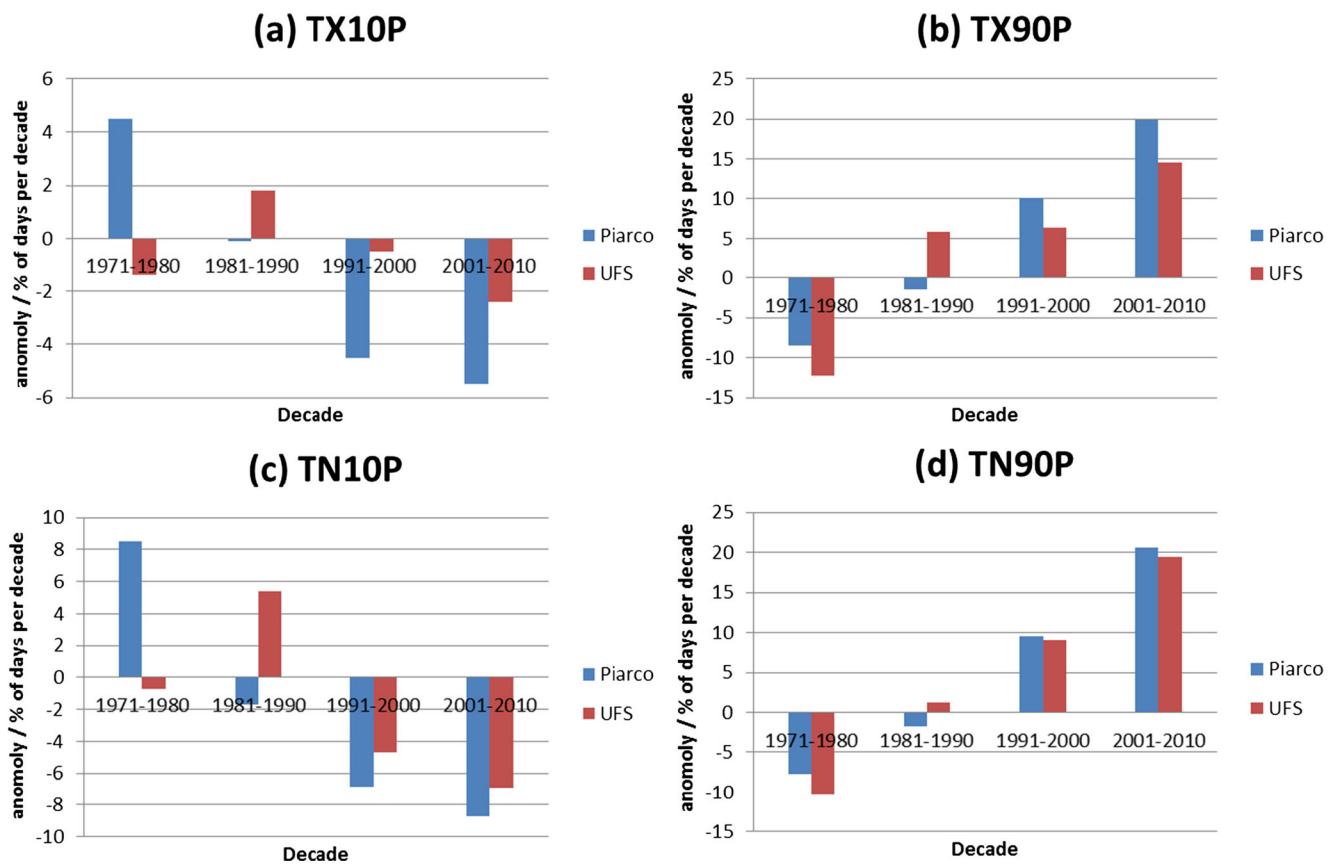
**Fig. 4** The decadal anomalies for frequencies of the number of cool days (TX10p), the number of warm days (TX90p), the number of cool nights (TN10p), and the number of warm nights (TN90p) for the period 1971–2010. The UFS decade is actually from 1972–1980

four other decades at Piarco showed drier than average rainfall. Table 4 summarizes the wettest and driest years for Piarco (1961–2010), UWI (1987–2010) and UFS (1972–2010). For UWI and the UFS, the wettest year was recorded in 1988 with 2206.1 and 2283.3 mm, respectively. Overall, the results suggest that there were no statistical significant temporal trends in precipitation (Table 5). Considering the wettest and driest years, UWI and UFS appeared to have similar local rainfall patterns.

## 4.4 Monthly precipitation extremes

The maximum 1-day precipitation (RX1day) was above normal at all three stations for the decade 2001–2010. At Piarco, there were three consecutive decades 1961 to 1990 for which the RX1day values were below average, and two decades 1991 to 2010 which were above normal. The RX1day patterns were different when compared with the maximum 5-day precipitation (RX5day) (Fig. 6). The RX5day anomaly was
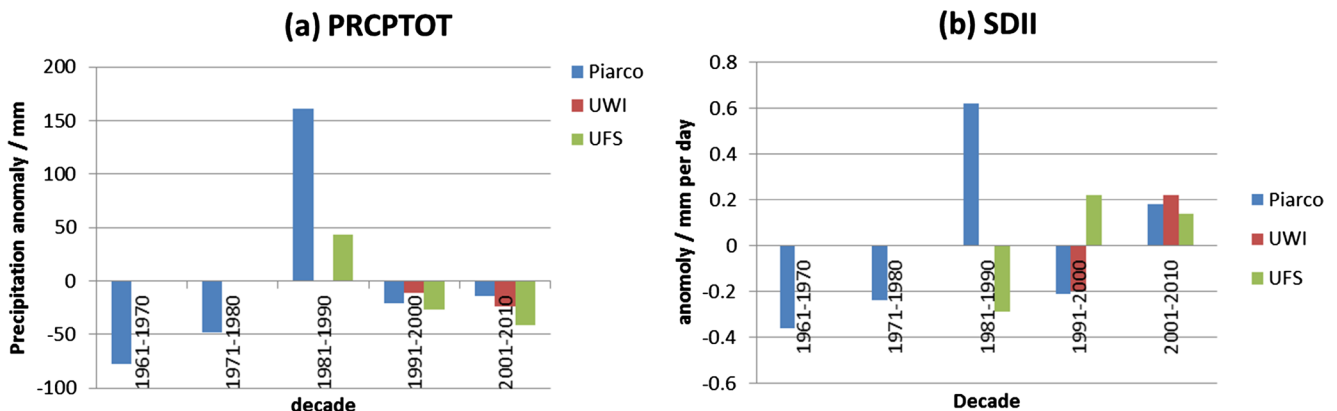


**Fig. 5** The annual precipitation (PRCPTOT) and the decadal simple intensity (SDII) anomalies for Piarco (1961–2010), UWI (1961–2010) and UFS (1973–2010)

**Table 4** Piarco (1961–2010), UWI (1961–2010) and UFS (1973–2010) wettest and driest years and the recorded precipitation

| Station | Wettest year (recorded amount/ mm) | Driest year (recorded amount/ mm) |
|---------|------------------------------------|-----------------------------------|
| Piarco | 1981 (2603.2) | 1987 (1454.4) |
| UWI | 1988 (2206.1) | 1977 (1119.2) |
| UFS | 1988 (2283.3) | 1977 (1094.0) |

above average for the decade 1981–1990 and which was the highest of the five decades investigated. It was noted that the highest 1-day rainfall amounts have increased over the last 20 years. At UWI, the annual RX5day precipitation increased by 24.5 mm per decade. The increased precipitation occurred during the dry season in both the RX1day and the RX5day at UWI and UFS (Table 5). These results indicated a higher intense rainfall in the dry season which would require further investigation using higher temporal resolution data.

4.5 Wet and heavy precipitation days

The simple daily precipitation intensity index (SDII) was used to describe the rainfall rates. There were no statistical significant monotonic trends at the 95 % level for the yearly and seasonal assessments of SDII (Table 5). Anomalies were significantly above average for Piarco in the decade 1981–1990 but below average for UFS. There were no linear trends in the total annual rainfall. The SDIIs were above average for all three stations in the 2001–2010 decade (Fig. 5b). Thus, it appears the number of wet days has decreased.

The extreme precipitation was assessed by the number of very wet days, R95p, and the number of extremely wet days,

R99p indices. These were based on the annual total precipitation which exceeded the 95$^{th}$ and 99$^{th}$ percentile thresholds. The number of annual extreme wet days significantly increased at a rate of 22.34 mm per decade, while there was no change in the very wet days. Although the annual R95p indicated no significant temporal trend; during the decades 1991–2010, the R95p anomalies were above average (Fig. 7), suggesting an increased intensity in those decades. Interestingly, the highest number of very wet days was recorded in the 1980s for all stations, while the years with the lowest number of wet days recorded were different at different stations, that is, in 1972 (Piarco), 1977 (UFS), and 2001 (UWI). The years with the highest R99p were 1981 (554.8 mm), 2006 (441.2 mm), and 2007 (441.2 mm) for Piarco, UFS and UWI, respectively. It was also observed that no extremely wet days were recorded in 6 years at Piarco during 1961 to 2003, 10 years from 1973 to 2009 at the UFS, and 7 years over the period 1989 to 2004 at the UWI. The decadal examination revealed that the decade 2001–2010 experienced the highest number of extremely wet days over the last five decades for Piarco.

The number of days with precipitation equal to or greater than 10 mm (R10) showed a similar pattern as the SDII, that is no linear trends, but above average heavy precipitation days at Piarco in the decade 1981–1990 and for all stations in the decade 2001–2010, as shown in Fig. 8a, b. The extreme precipitation was defined by the amount of rainfall equivalent to the 95$^{th}$ percentile of the time series. The 95$^{th}$ percentiles are as follows: for Piarco, 25.8 mm; for UFS, 23.4 mm; and for UWI, 23.8 mm. Thus, the number of days with precipitation equal to or greater than 20 mm, that is R20, is a closer representation of the very wet days in this tropical convective region as noted by Peterson et al. (2002). Apparent increasing trends for R10, RX1day, and R95p were noted however, these were not statistically significant.

**Table 5** Annual and seasonal trends of the extreme indices of the precipitation for Piarco, UFS, and UWI stations, Trinidad

| Indices | Unit | Piarco (1961–2010) | | | UFS (1972–2010) | | | UWI (1987–2010) | | |
|---------|------|--------|------|------|--------|------|------|--------|------|------|
| | | Annual | Dry | Wet | Annual | Dry | Wet | Annual | Dry | Wet |
| PRCPTOT | mm per decade | 17.32 | – | – | 0.08 | – | – | 25.40 | – | – |
| R95p | | 12.85 | – | – | −17.86 | – | – | −2.94 | – | – |
| R99p | | 16.01 | – | – | 1.63 | – | – | 69.30 | – | – |
| RX1day | | 2.36 | 0.06 | 1.11 | 0.58 | *2.92* | −0.79 | 6.60 | *8.60* | −2.02 |
| RX5day | | 5.07 | 0.57 | 0.69 | 0.50 | *5.98* | −2.73 | *24.50* | 7.76 | 0.92 |
| SDII | mm/day | 0.11 | – | – | 0.21 | – | – | 0.19 | – | – |
| R10 mm | days per decade | 0.56 | – | – | 1.00 | – | – | 0.00 | – | – |
| R20 mm | | 0.00 | – | – | 0.00 | – | – | 0.00 | – | – |
| CWD | | 0.00 | – | – | 0.00 | – | – | 0.00 | – | – |
| CDD | | 1.02 | – | – | 2.00 | – | – | 1.25 | – | – |

Values set in italics represent 95 % significant level ($p<0.05$)

## (a) RX1day



## (b) RX5day



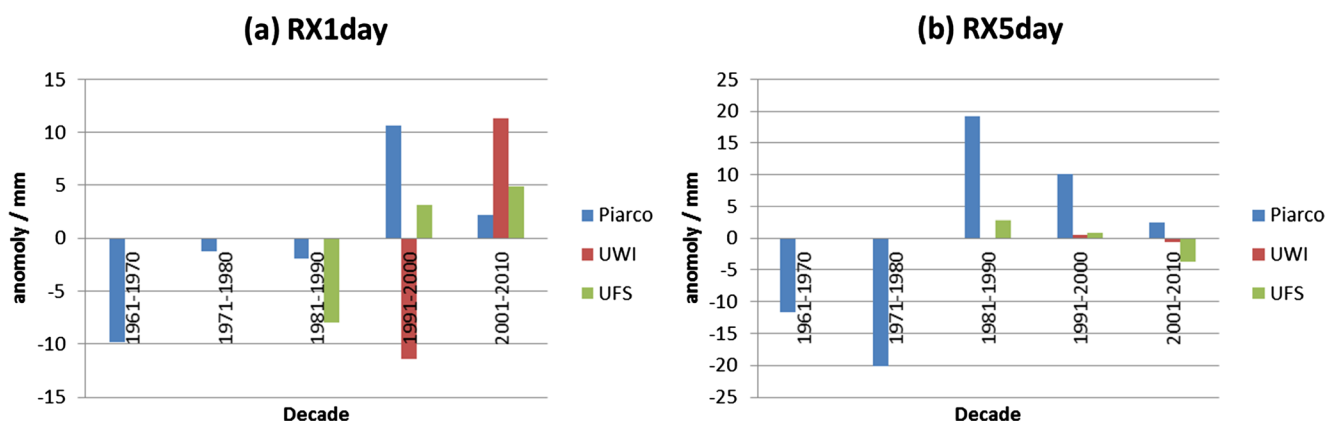**Fig. 6** Decadal anomalies for the annual maximum 1 day (RX1day) and 5 day (RX5day) precipitation for Piarco, UWI, and UFS

### 4.6 Consecutive dry days and consecutive wet days

There were no indications of a significant trend in the annual number of consecutive dry days (CDD); however, for all three stations in the decade 2001–2010, the numbers of CDD were higher than the previous decade (Fig. 8c). The highest CDD were recorded in 1966, 1987, and 2003, with the number of days varying among the stations. At Piarco in 1966, there were 44 consecutive days with less than 1 mm of rainfall recorded, while for Piarco, UFS, and UWI in 1987, there were 46, 60, and 59 CDD; and in 2003, there were 50, 67, and 58 CDD, respectively. Similar to the CDD, there were no significant trends in the annual number of consecutive wet days. There was an unusual occurrence of a wet spell in the last month of the dry season in 1983 with 23 consecutive wet days during 8th–30th of May at Piarco. This clearly requires further investigation. Excluding 1983, the CWD annual mean for the 80s was 11 days.

### 4.7 Model comparisons

This section compares the findings for the Caribbean region from two global and one regional climate outlooks, under different scenarios. There are four basic scenarios, the A1

and A2 scenarios which are economically centered, while B1 and B2 are environmentally focused. Simultaneously, A1 and B1 represent globalization, while A2 and B2 focuses on regions (IPCC 2000). For the global viewpoints, the Coupled Model Intercomparison Project Phase 3 (CMIP3) and a 20-km atmospheric general circulation model were used, while for the regional aspect the Hadley Centre Providing Regional Climates for Impact Studies for the Caribbean (PRECIS-Caribe) was utilized.

Projections for the Caribbean region were well captured by the PRECIS model, for the period 2071–2100 relative to 1961–1990 (Campbell et al. 2011). For the southern Caribbean for which Trinidad is a part, under the A2 scenario which considers a region and the economic development, there was a temperature projection of 2.0 to 5.0 °C increase. In a more recent report, a 20-km atmospheric general circulation model was used to project the Caribbean climate for the period 2073–2099 for the A1B scenario which represents the economical global aspect (IPCC 2000 and Hall et al. 2013). Similar patterns of increased temperatures were estimated for the Caribbean region and for Trinidad the model projected increases in the annual and seasonal temperatures by 2.0 °C (Hall et al. 2013). In addition, the frequency of warm days was projected to increase by 2–3 days over the Southern Caribbean
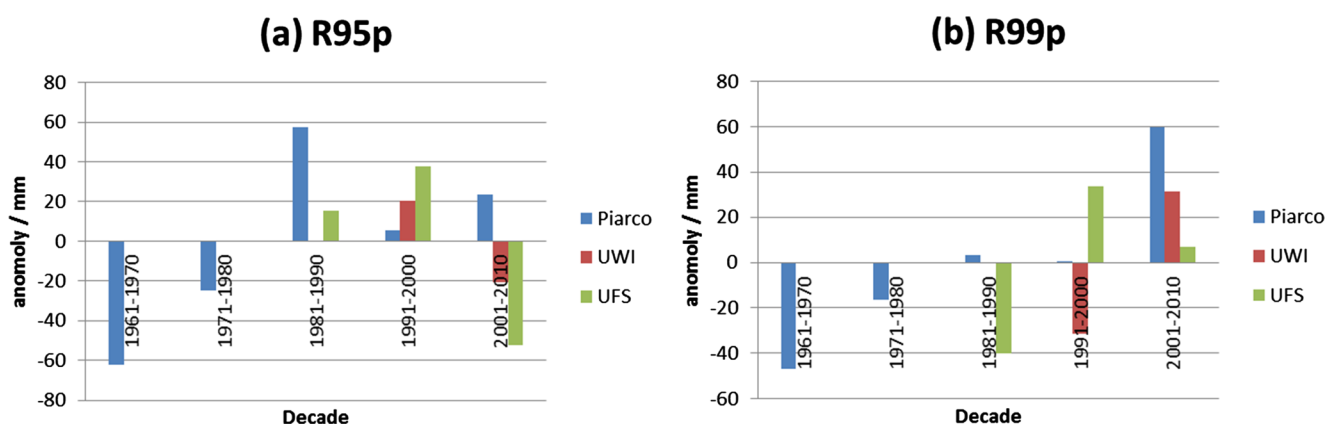
## (a) R95p



## (b) R99p



**Fig. 7** Decadal anomalies for the average very wet days (R95p) and extremely wet days (R99p) for Piarco, UWI, and UFS

(Hall et al. 2013). The estimates of another global perspective, the CMIP3 model for the A2 scenario for the year 2080, were for warmer annual surface air temperatures between 2.50 and 2.75 °C (Karmalkar et al. 2013). In our study, the surface air temperature over Trinidad was found to have increased by 0.1 °C per decade. If we consider that similar warming rates continues, then this will agree well with the warming pattern of the model projection under the A2, B2, and A1B scenarios. Our results indicated that the number of extremely hot days significantly increase which agree well with the projected pattern of an increase temperature both globally and regionally.

For Trinidad, it was found that there were decreasing precipitation trends at one meteorological station, St Ann's for the period 1862–1977 which were experienced in the months of May, June, and July, in addition to the annual rainfall, dry season, and wet season (Beharry et al. 2013). For Piarco, in the UWI and the UFS, there were no significant trends for the period 1961–2010, as seen in Beharry et al. (2013) and in the rainfall indices in our study. The decreasing trends for the St. Ann's station covered 116 years which ended in 1977 follow the pattern of the regional and global projections for Trinidad under economical, global, and regional factors. The precipitation in Trinidad under the A2 scenario

projected that during November, December, January, February, March, and April, less rainfall is expected to be received (Campbell et al. 2011) which agrees with the projections under the A1B scenario of an estimated decrease in the mean annual rainfall by 10 % (Hall et al. 2013). However, the CMIP3 model for the A2 scenario estimates that for the year 2080, the precipitation varied with an expected wetter May, June, and July by 30–40 %, and a drier August, September, October, and November by 20–30 % (Karmalkar et al. 2013).

The extreme precipitation events are also expected to experience changes such that the Southern Caribbean would be characterized by less intense rainfall and more dry days (Campbell et al. 2011). It was also projected that the Caribbean SDII will increase by at least 15 % in the southern region and the number of consecutive dry days will decrease (Hall et al. 2013). Our decadal analysis suggest that for the decade 2001–2010, there were above normal SDII, although we found no statistical significant temporal trend in the annual and seasonal analyses. It was noted that under the different scenarios, the trends for the number of dry days differed. As for the CCDs, the decade 2001–2010 showed above normal pattern which agrees with one of models' projection of an increase number CDD in Campbell et al. (2011). Overall, for both temperature and precipitation the global, regional, and
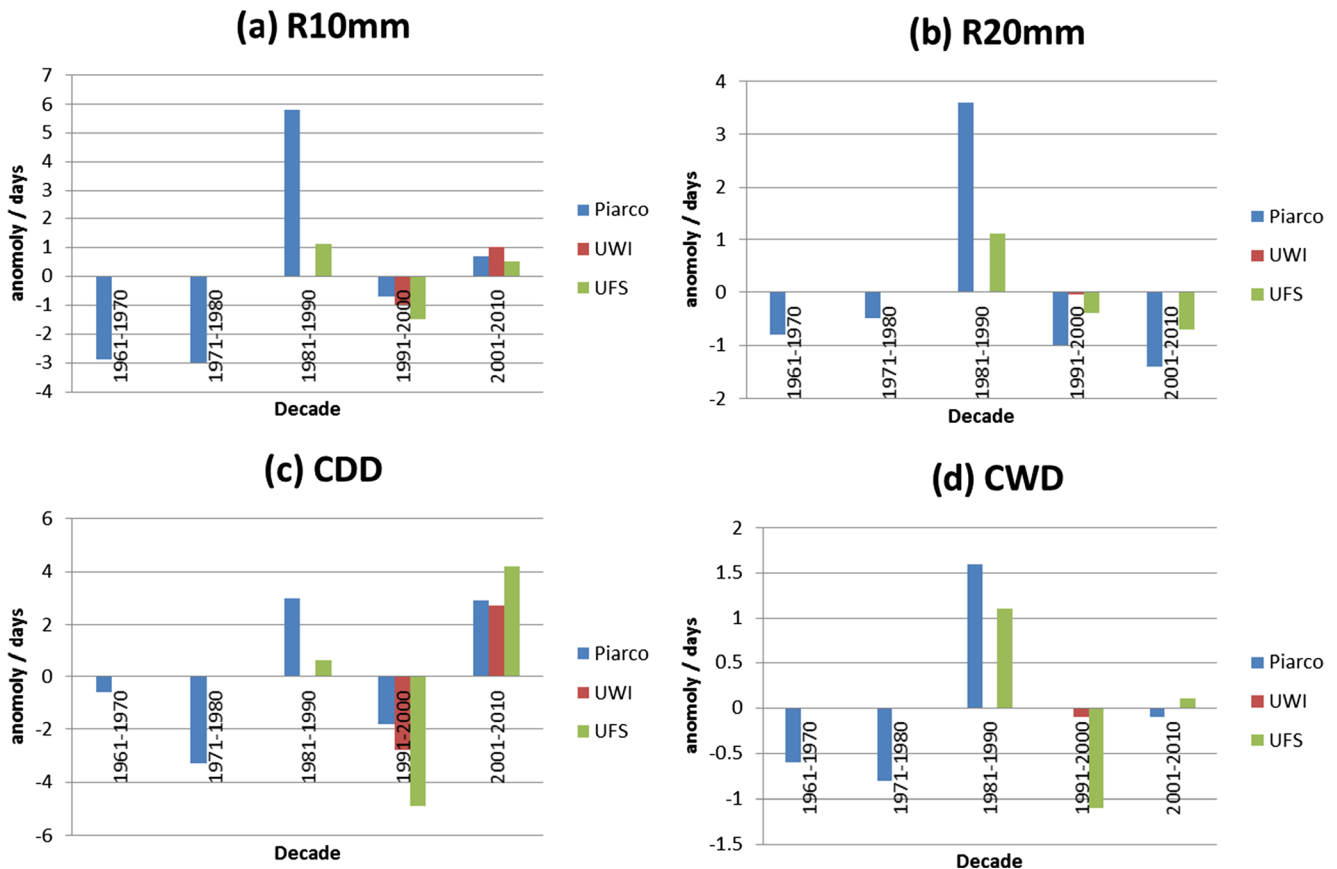


Fig. 8 Decadal anomalies for the number of heavy precipitation days (R10mm), the number of very heavy precipitation days (R20mm), the number of consecutive dry days (CDD), and the number consecutive wet days (CWD) for Piarco, UWI, and UFS

local projections suggest increased temperatures and decreased precipitation.

## 5 Discussion

The maximum and minimum temperatures in Trinidad showed a general significant warming trend which is in agreement with the Caribbean region and global patterns (Peterson et al. 2002; Donat et al. 2013 and Stephenson et al. 2014). Our study also suggests that the nighttime warming was greater than the daytime warming, which are similar to the warming patterns detected in South America (Vincent 2005), Europe (Elguindi, et al. 2013), and globally (Alexander et al. 2006). It was observed that the rates of warming were not the same for the two stations and that the warming at Piarco was greater than that at the UFS. No metadata were available to assist in the understanding of the difference in results, and the general details of the stations surroundings were different. The Piarco meteorological data were recorded at an international airport with buildings adding to the heat and natural flow of the wind, whereas the UFS station data were gathered in an agricultural field station. Due to limited data, no adjustments were made to the data to standardize the effect of the influence of different surroundings.

Other common findings in the temperature analyses were the increase in the number of warm days and nights and the decrease in the number of cool days and nights. For the Caribbean region, the rate of increase for the warmest day and night temperatures TXx and TNx were 0.27 and 0.23 °C per decade, respectively, while the rate of decrease for the coolest day and night temperatures TXn and TNn were 0.18 and 0.32 °C per decade, respectively (Stephenson et al. 2014). Furthermore, locally, the range of the warmest day and night increase and the range of the coolest day and night decrease appear to be greater in the island of Trinidad compared with that of the Caribbean region. Seasonal analyses were performed in our study, and it was found that the changes were different in the dry and wet seasons in Trinidad for the warm days and nights and the cool days and nights. For example, consider the UFS station where the annual percentage of the number of warm days increased; however, during the wet season the increase in the percentage of days per decade was approximately twice that of the dry season (Table 3). Thus, there was therefore a greater warming in the wet season compared with the dry season and there are implications for agriculture, tourism, and the available water resources.

The decadal analyses for all the temperature indices highlighted above average anomalies since the decade 1981–1990. Significantly, the lowest minimum temperatures appear to have increased at a higher degree inferring that there are less cool nights, which were reflected in both the annual

and seasonal analyses. These local trends of a greater percentage of warm days and nights and the lesser cool days and nights, for Trinidad, are similar to those for the wider Caribbean region (Peterson et al. 2002 and Stephenson et al. 2014) and globally (Donat et al. 2013). Globally, there is evidence to indicate a positive shift in the temperature extremes, in particular with the indices derived from daily minimum temperature, over the whole 110 years of record, but with stronger trends in more recent decades (Donat et al. 2013). Our results also showed a positive shift in the temperature indices TXx, TXn, TNx, TNn, TX90p, and TN90p that began in 1980s.

There were no statistically significant trends for the annual precipitation indices for Trinidad, which follow those of the Caribbean regions annual total precipitation and the simple daily intensity index (Stephenson et al. 2014). Our decadal analysis, however, highlighted some apparent changes in Trinidad's precipitation indices. In the decade 1981–1990, the annual precipitation was above normal at Piarco with the SDII, the number of very heavy rainfall days and the number of consecutive wet days being the highest in this decade among the five decades. Globally, the wettest decade was 2001–2010 (WMO 2013), whereas in our study, the wettest decade was 1981–1990. This is reasonable considering the spatial scales and global averaging thus, emphasizing the need for local scale studies like ours. Additionally, according to WMO, globally the wettest recorded year was 2010 (WMO 2013), whereas at Piarco, UFS, and UWI, the year 2010 was the 5th, 2nd, and 6th wettest recorded year, respectively, for different periods studied. For Trinidad, the SDII appeared to have increased in the decade 2001–2010, but there was no apparent change in the annual precipitation, which suggests that the number of wet days has decreased. However, we need to note that a wet day was one with rainfall equal to or greater than 1 mm which may not be applicable to the tropical Caribbean region. The decadal approach also suggested that the extremely wet days, that is days with precipitation greater than approximately 24 mm, have increased in the decade 2001–2010. These findings are therefore an indication that there was a shift in the rainfall patterns, such that the number of wet days has decreased, but the wet days have been receiving more rainfall than normal in the decade 2001–2010. The implication of such a shift in rainfall patterns may increase the probability of flash flooding and can also impact on agriculture and infrastructure. The examination of extreme precipitation acts as a first approximation in the indication of increased (decreased) heavy rainfall as a result of the increased (decreased) precipitation amounts (Groisman et al. 1999), and further assessment is necessary.

For Trinidad, it appears that the daily rainfall patterns are changing due to the above normal RX1day rainfall in the last two decades. Comparing the decades 1991–2000 and 2001–2010 at the UWI station, there were no significant difference

in the number of days with rainfall above 20 mm; however, at Piarco there was below average R20 for the decade 2001–2010, relatively drier compared with the 1991–2000 decade (Fig. 8b). This difference may be due to localized weather conditions and possible microclimates, again highlighting the need for local studies given that regional and global studies present findings based on area averaging. The area averaging therefore masks the influence of such microclimate effects in the results. The outcomes of local studies are valuable in vulnerability and adaptation assessments for small tropical island states or in larger countries where there may be different climates.

Globally, since 1901–2010, the number of heavy precipitation days has been less frequent and the average intensity of daily precipitation has decreased, but in the last 60 years (1951–2010), they both have increased (Donat et al. 2013). These global patterns for the last 60 years were not observed for Trinidad for the 50 years investigated; however, in the decade 2001–2010, the SDII was higher than average suggesting more intense rainfall events. Additionally, in the decade 2001–2010, the number of consecutive dry days was higher than the previous decade 1991–2000 at all three stations. Interestingly, 2010 was reported as the wettest recorded year globally. The apparent positive shift in the CDD in Trinidad may be attributed to effects of the meteorological drought experienced during January to March in 2010 in Trinidad and other neighboring Caribbean islands (Trotman et al. 2010). In 2010, the numbers of CDD in the dry season were 48 (Piarco), 87 (UFS), and 59 (UWI). In the Caribbean region, it was observed that the CDD patterns are dependent on the period investigated since Peterson et al. (2002) reported less CDD, and more recently, Stephenson et al. (2014) and the model projections (Hall et al. 2013) found that the CDD appears to be increasing. Globally, for 1951–2010, there was a significant decreasing decadal CCD trend by 1.66 days (Donat et al. 2013).

Globally, Donat et al. (2013) reported that changes in precipitation extremes are spatially less consistent compared with temperature indices. It should therefore be emphasized that the findings of our precipitation extreme weather study was based on a local scale with stations in a high spatial density for one region of Trinidad and these features discovered maybe be different from regional and global analyses.

Comparing the Caribbean island temperature trend with the global and regional patterns, we see a general warming. For the precipitation in the dry season, it was projected that the rainfall would be less intense and accompanied by more dry days; however, our results suggest that the dry season rainfall will be more intense with more dry days. Although there were no statistical significant trends that the precipitation is decreasing, there are apparent changes within the decades.

## 6 Summary

Our study presents trends and patterns of indices of temperature and precipitation for Trinidad for 1961–2010 using the RClimDex software and the Mann-Kendall test. Two temperature stations and three precipitation stations were used in the investigation due to the limited high quality datasets. The data was assessed annually, seasonal, and decadal and compared with a regional climate model, a 20-km atmospheric global circulation model and projections of CMIP3. It was found that there was a significant general warming in the annual mean of the daily maximum and minimum temperatures. The wet season appears to be warming faster than the dry season; however, in both seasons, the nighttime warming is greater than the daytime warming. Our results also suggested that Trinidad has experienced more warm days and fewer cool nights during the period 1963 to 2010.

For all the annual precipitation indices with the exception of the extremely wet days, there were no statistical significant trends. Seasonally, the monthly extremes assessment provides the evidence in the trends from the 5 day maximum precipitation that the dry season is experiencing a higher intense rainfall. The decadal assessment highlighted the decade, 1981–1990 for above annual maximum 5-day precipitation, very wet days, the number of heavy precipitation days, the number of very heavy precipitation days, and the number consecutive wet days. In addition, there were above average anomalies for the SDII, annual maximum 1-day precipitation, extremely wet days, and the number of consecutive wet days in the decade 2001–2010.

## References

Abbas Farhat, et al. (2013) Changes in precipitation extremes over arid to semiarid and subhumid Punjab, Pakistan. Theoretical and Applied Climatology:1-10. doi: 10.1007/s00704-013-0988-8

Aguilar E et al (2005) Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. J Geophys Res Atmos 110, D23107. doi:10.1029/2005JD006119

Alexander LV et al (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111, D05109. doi:10.1029/2005JD006290

Beharry S (2012) Analyses of rainfall, temperature and related extreme events for Trinidad and Tobago. Master of Philosophy, University of the West Indies, St. Augustine, Trinidad

Beharry SL, Clarke RM, Kurmarsingh K (2013) Precipitation trends using in-situ and gridded datasets. Theor Appl Climatol. doi:10.1007/s00704-013-0921-1

Campbell JD, Taylor MA, Stephenson TS, Watson RA, Whyte FS (2011) Future climate of the Caribbean from a regional climate model. Int J Climatol 31:1866–1878. doi:10.1002/joc.2200

Chen A, Taylor MA (2002) Investigating the link between early season Caribbean rainfall and the El Niño+1 year. Int J Climatol 22(1):87–106. doi:10.1002/joc.711

Chu P-S, Chen YR, Schroeder TA (2010) Changes in precipitation extremes in the Hawaiian islands in a warming climate. Journal of. Climate, 23, 4881–4900. doi: http://dx.doi.org/10.1175/2010JCLI3484.1

Donat MG et al (2013) Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: the HadEX2 dataset. J Geophys Res Atmos 118:2098–2118. doi:10.1002/jgrd.50150

dos Santos CAC, Neale CMU, Rao TVR, da Silva BB (2011) Trends in indices for extremes in daily temperature and precipitation over Utah, USA. Int J Climatol 31:1813–1822. doi:10.1002/joc.2205

Dufek AS, Ambrizzi T (2008) Precipitation variability in São Paulo State, Brazil. Theor Appl Climatol 93(3–4):167–178. doi:10.1007/s00704-007-0348-7

Easterling DR, Alexander LV, Abdallah Mokssit, Valery Detemmerman (2003) CCI/CLIVAR workshop to develop priority climate indices" Bulletin of the Mathematical Society 84, 1403–1407. doi: http://dx.doi.org/10.1175/BAMS-84-10-1403

ETCCDMI (2013) ETCCDMI/CRD Climate Change Indices, Software. Accessed 3March 2014. http://etccdi.pacificclimate.org/software.shtml

Fan X, Wang Q, Wang M (2012) Changes in temperature and precipitation extremes during 1959–2008 in Shanxi, China. Theor Appl Climatol 109(1–2):283–303. doi:10.1007/s00704-011-0577-7

Garstang M (1959) Tropical island rainfall: a study of the rainfall distribution of Trinidad, West Indies. Woods Hole Oceanographic Institution

Gocic M, Trajkovic S (2013) Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. Glob Planet Chang 100:172–182

Granger OE (1982) Climatic fluctuations in Trinidad west indies and their implications for water resource planning. Caribb J Sci 17:173–201

Groisman PY et al (1999) Changes in the probability of heavy precipitation: important indicators of climatic change. Clim Chang 42:243–283

Hall TC, Andrea M, Sealy TS, Stephenson SK, Taylor MA, Chen AA, Kitoh A (2013) Future climate of the Caribbean from a super-high-resolution atmospheric general circulation model. Theor Appl Climatol 113(1–2):271–287. doi:10.1007/s00704-012-0779-7

Hamed KH (2008) Trend detection in hydrologic data: the Mann–Kendall trend test under the scaling hypothesis. J Hydrol 349(3):350–363

Haylock, M. R., et al. (2006) Trends in total and Extreme South American rainfall in 1960–2000 and links with sea surface temperature. Journal of Climate, 19, 1490–1512. doi:10.1175/JCLI3695.1

Insaf TZ, Lin S, Sheridan SC (2013) Climate trends in indices for temperature and precipitation across New York State, 1948–2008. Air Qual Atmos Health 6(1):247–257. doi:10.1007/s11869-011-0168-x

IPCC (2007) Summary for Policymakers. In: Climate change 2007: the physical science basis. contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2013) Summary for Policymakers. In: Climate change 2013: the physical science basis. contribution of working group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker,T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley

(eds.)].Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jury M, Malmgren BA, Winter A (2007) Subregional precipitation climate of the Caribbean and relationships with ENSO and NAO. J Geophys Res 112, D16107. doi:10.1029/2006JD007541

Karmalkar AV, New M, Taylor MA, Campbell J, Stephenson T et al (2013) A review of observed and projected changes in climate for the islands in the Caribbean. Atmosfera 26(2):283–309

Klein Tank AMG et al (2006) Changes in daily temperature and precipitation extremes in central and south Asia. J Geophys Res 111, D16105. doi:10.1029/2005JD006316

Neelin JD, Munnich M, Su H, Meyerson JE, Holloway C (2006) Tropical drying trends in global warming models and observations. Proc Natl Acad Sci 103:6110–6115

New M et al (2006) Evidence of trends in daily climate extremes over southern and west Africa. J Geophys Res 111, D14102. doi:10.1029/2005JD006289

Peterson TC (2005) The workshop on enhancing south and central Asian climate monitoring and indices. Pune, India, February 14–19, 2005, CLIVAR Exch., 10, 6

Peterson TC, et al (2002) Recent changes in climate extremes in the Caribbean region. Journal of Geophysical Research: Atmospheres. 107 (D21): ACL 16-1-ACL 16-9.

Santos, Carlos Antonio Costa dos (2011) Trends in indices for extremes in daily air temperature over Utah, USA. Revista Brasileira de Meteorologia 26:19-28

Seepersad J (1977) An analysis of droughts in Trinidad. B. Sc. Thesis. McGill University

Sensoy S, Peterson TC, Alexander L, Zhang X (2007) Meeting summary: enhancing Middle East climate change monitoring and indexes. 88: 1249-1254

Singh B (1997) Climate-related global changes in the Southern Caribbean: Trinidad and Tobago. Glob Planet Chang 15(3–4):93

Skansi M.et al (2013) Warming and wetting signals emerging from analysis of changes in climate extreme indices over South America. Global and Planetary Change no. 100 (0):295-307. doi:10.1016/j.gloplacha.2012.11.004.

Stephenson TS et al (2014) Changes in extreme temperature and precipitation in the Caribbean region, 1961–2010. Int J Climatol. doi:10.1002/joc.3889

Stone RJ (2001) Changing seasonal rainfall patterns in Trinidad: myth or reality. West Indian J Eng 23(2):9–16

Stone R (2008) The alleged surface air temperature rise in Trinidad: climate change or thermometer change? The16th CAS Biennial Conference on Science and Technology Vehicles for Sustainable Economic Development in the Caribbean; 11-13 October 2008. 296-301

Tabari H, Hosseinzadeh Talaee P (2011) Analysis of trends in temperature data in arid and semi-arid regions of Iran. Glob Planet Chang 79(1): 1–10

Tabari H, Talaee PH (2011) Temporal variability of precipitation over Iran: 1966–2005. J Hydrol 396(3):313–320

Trinidad and Tobago meteorological services (2009) climate: the geography and climate of Trinidad and Tobago Accessed May 25, 2009. http://www.metoffice.gov.tt/climate/article.aspx?id=4820.

Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A (2007) Observations: surface and atmospheric climate change. In: Climate change 2007. In: Solomon SD, Qin M, Manning Z, Chen M, Marquis KB, Tignor AM, Miller HL (eds) The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, ambridge, United Kingdom and New York, NY, USA

Trinidad and Tobago. Central Statistical Office (CSO). (2012) Country Introduction. Chapter 1. Accessed May 5 2012. http://www.cso.gov.tt/files/statistics/Chapter%201.pdf.

Trinidad and Tobago. Water Resources Agency (2001) Integrating the management of watersheds and coastal areas in Trinidad and Tobago. Prepared by the Water Resource Agency for the Ministry of the Environment, Complex Independent Square, Port of Spain. Assessed 12 May 2013. http://www.oas.org/reia/IWCAM/pdf/Trinidad%20and%20Tobago/Trinidad%20and%20Tobago%20National%20Report.PDF.

Vincent LA (2005) Observed trends in indices of daily temperature extremes in South America 1960–2000. Journal of Climate 18: 5011–5023. doi:10.1175/JCLI3589.1

Vincent L(2012) Calculating climate indices using RClimDex. Last assessed 3 February 2014. http://www.google.tt/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&ved=0CCoQFjAB&url=http%3A%2 F%2Fetccdi.pacificclimate.org%2FRClimDex%2FRClimDexUserManual.doc&ei=C Q X 9 U v z R G 9 H u k Q f t m Y C w A g & u s g =AFQjCNFHk5A6R5v1xANSoQK9O1s_DuVRUQ&bvm=bv.61190604,d.eW0

Wang XL (2008) Penalized maximal F test for detecting undocumented mean shift without trend change. J Atmos Ocean Technol 25:368–384

Wang XL, Wen QH, Wu Y (2007) Penalized maximal t-test for detecting undocumented mean change in climate data series. J Appl Meteorol Climatol 46:916–931

Wang H et al (2013) Changes in daily climate extremes in the arid area of northwestern China. Theor Appl Climatol 112(1–2):15–28. doi:10.1007/s00704-012-0698-7

Wehekind L and Smith GW (1955) Trinidad rainfall, 1933-1952 and rainfall reliability. Government Printery Office. Trinidad, British West Indies

World Meteorological Organization (WMO) (2013) The global climate 2001-2010: a decade of climate extremes. Accessed July 7, 2013. http://library.wmo.int/pmb_ged/wmo_1103_en.pdf.

Zhang X et al (2005) Trends in middle east climate extreme indices from 1950 to 2003. J Geophys Res 110, D22104. doi:10.1029/2005JD006181