# 3. RAINFALL & TEMPERATURE

## 3.1. INTRODUCTION

In this chapter the historical monthly climatology (i.e. the mean value for each month over a period of several years) as well as recent trends in mean and extremes of rainfall and temperature are presented. The results provided are for indices averaged over (i) the Caribbean region as a whole (see Figure 3.1 for domain definitions), (ii) six defined climatic zones (also see Figure 3.1), and (iii) the 19 BMCs of the CDB listed in Table 3.1.

**Table 3.1**: The 19 Borrowing Member Countries (BMCs) of the Caribbean Development Bank (CDB).

| | COUNTRIES | CAPITAL | LATITUDE | LONGITUDE | RAINFALL ZONE | DATA PERIOD |
|---|---|---|---|---|---|---|
| 1 | ANGUILLA | The Valley | 18.220833 | -63.051667 | 5 | 1993 to 2017 |
| 2 | ANTIGUA AND BARBUDA | St. John's | 17.116667 | -61.85 | 5 | 1971 to 2017 |
| 3 | BARBADOS | Bridgetown | 13.105833 | -59.613056 | 5 | 1971 to 2017 |
| 4 | BELIZE | Belmopan | 17.251389 | -88.766944 | 1 | 1979 to 2017 |
| 5 | BRITISH VIRGIN ISLANDS | Road Town | 18.431389 | -64.623056 | 4 | - |
| 6 | CAYMAN ISLANDS | George Town | 19.3034 | -81.3863 | - | 1971 to 2017 |
| 7 | DOMINICA | Roseau | 15.301389 | -61.388333 | 5 | 1971 to 2017 |
| 8 | GRENADA | St. George's | 12.05 | -61.75 | 5 | 1986 to 2017 |
| 9 | GUYANA | Georgetown | 6.801111 | -58.155278 | 6 | 1971 to 2017 |
| 10 | HAITI | Port-au-Prince | 18.533333 | -72.333333 | 4 | 1971 to 2017 |
| 11 | JAMAICA | Kingston | 17.983333 | -76.8 | 3 | 1971 to 2017 |
| 12 | MONTSERRAT | Plymouth | 16.706417 | -62.215839 | 5 | - |
| 13 | ST KITTS AND NEVIS | Basseterre | 17.3 | -62.733333 | 5 | 1972 to 2017 |
| 14 | ST LUCIA | Castries | 14.016667 | -60.983333 | 5 | 1971 to 2017 |
| 15 | ST VINCENT AND THE GRENADINES | Kingstown | 13.157778 | -61.225 | 5 | 1979 to 2017 |
| 16 | SURINAME | Paramaribo | 5.852222 | -55.203889 | 6 | 1971 to 2017 |
| 17 | THE BAHAMAS | Nassau | 25.06 | -77.345 | 3 | 1971 to 2017 |
| 18 | TRINIDAD AND TOBAGO | Port of Spain | 10.666667 | -61.516667 | 5 | 1971 to 2017 |
| 19 | TURKS AND CAICOS ISLANDS | Cockburn Town | 21.459 | -71.139 | - | - |

Figure 3.1 outlines the general geographical region (Caribbean domain) which is the focus of this report as well as the locations of the 19 BMCs listed in Table 3.1 and their capital cities (red dots). For averaging over the entire Caribbean, the purple box roughly defines the boundaries used (approximately 5N to 25N and 60W to 90W). The Caribbean-wide index is defined to be consistent with the analysis of previous studies (see for example Giannini et al. 2000; Taylor et al. 2002), thereby facilitating easy comparisons with their findings. The Caribbean region is also divided into six rainfall zones (numbered 1 to 6) with similar rainfall patterns. The zones used in this study are adapted from a number of other studies which use a variety of statistical techniques to group countries with similar rainfall climatological patterns (see for example the studies of Jury et al. 2007; McLean et al. 2015; Stennett-Brown et al. 2017; Martinez et. al. 2019). Figure 3.1 also displays the annual climatology of rainfall (bar graphs in blue) and temperature (line graph in red) for each of the six defined zones. The graphs show that there are general similarities as well as distinct features in both the temperature and rainfall patterns for each of the six zones. In the following sections the data sets and the climatologies for the Caribbean and the six zones are further discussed.

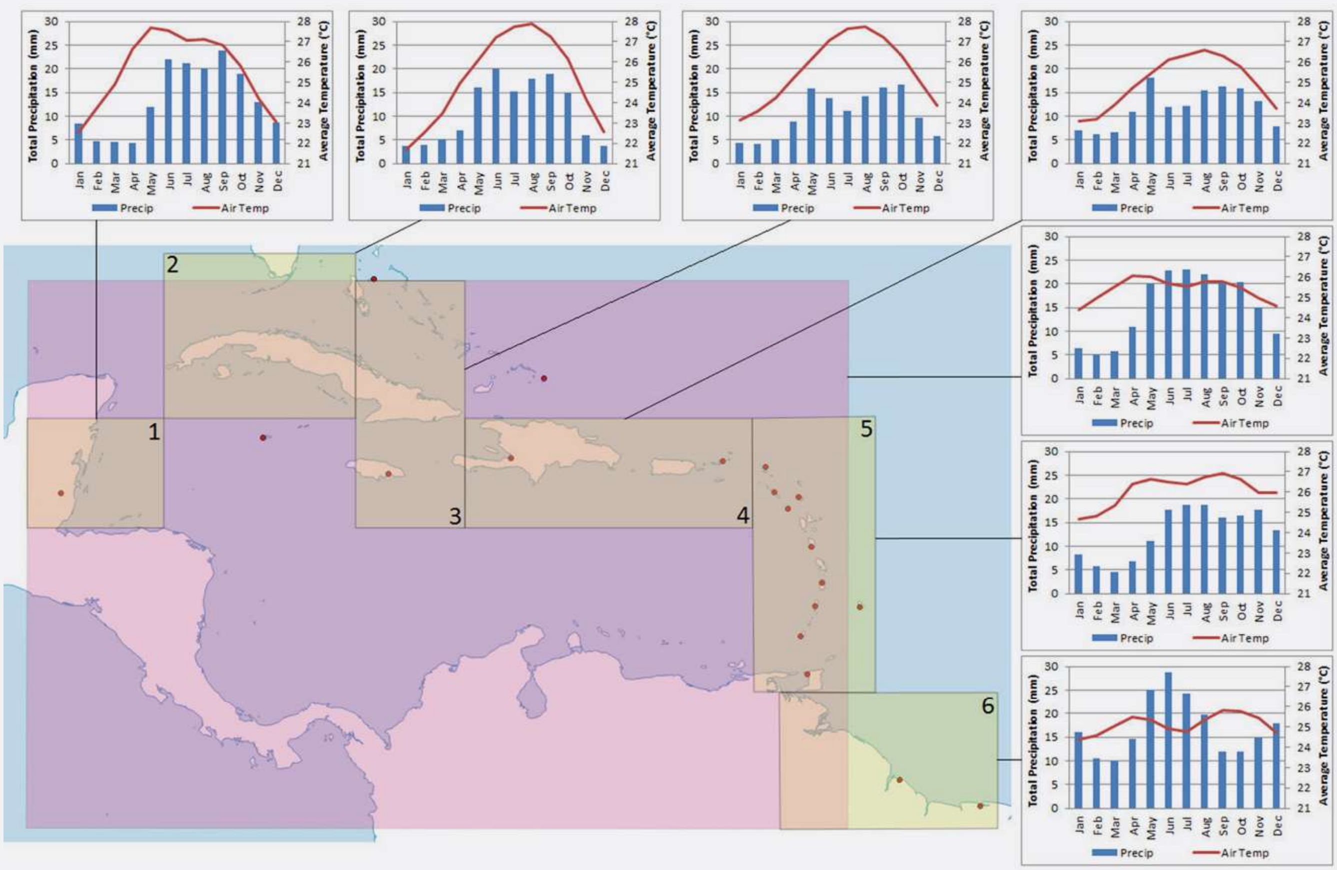



**Figure 3.1:** Map showing: (i) The Caribbean Domain, (ii) The 6 Rainfall Zones, (iii) The location of the CDB BMCs and their capital cities and, (iv) The Rainfall and Air Temperature Climatologies for each of the six defined zones (averaging period: 1980-2014).

## 3.2. CARIBBEAN RAINFALL

In this section, the rainfall climatologies of the Caribbean region and the six rainfall zones are discussed. The section also presents an analysis of historical precipitation looking at both: (i) the time scale decomposition of the rainfall time series, (ii) trends in the amount of rainfall received in the Caribbean as a whole and in each zone, and (iii) trends in precipitation extremes defined using extreme indices.

Data from the University of Delaware (UDel) dataset (Willmott et al. 2001) averaged over the period 1980-2014 were used to produce the climatological rainfall (and temperature) graphs for the Caribbean as a whole and for the six zones. (Details of the datasets used in all analyses are provided in Chapter 2.) The UDel dataset was chosen for its relatively high resolution and because it contained both rainfall and temperature data. Time scale decomposition of the historical rainfall data was done utilising the International Research Institute (IRI) Climate and Society Map Room Tool (Greene et al. 2011). This tool utilises the Climate Research Unit (CRU) dataset ((Harris et al. 2014)) due to its longer available time series.

Country-specific analysis was conducted using station data from a single station in each country listed in Table 3.1. The use of a single station is to be borne in mind when interpreting the country results. The station data were obtained through the CAROGEN portal (see again Chapter 2).

### 3.2.1. RAINFALL CLIMATOLOGY

Figure 3.2 presents the rainfall climatology pattern of the Caribbean averaged as a whole and for the six defined rainfall zones given in Figure 3.1. The following things are noted:

- The figure shows that the Caribbean has a wet season which runs from May to November and a dry season that runs from December to April. Rainfall during the wet season accounts for approximately 70% of each zone's total precipitation.
- Across most zones, the wet season has a distinctive bi-modal pattern with a rainfall peak in May or June and another which falls between September and December (Zone 6). This gives rise to the four rainfall periods often used to describe the climate of the Caribbean, namely: the Early Dry Season (December-April), the Early Rainfall Season (May-June), the Mid-Summer Drought or MSD (July-August), and the Late Rainfall Season (September-November). The bi-modal pattern and the resulting dry and wet seasons are defining climatological features of the Caribbean region.
- The timing of peaks in rainfall varies depending on rainfall zone. Zone 6 (the far south Caribbean inclusive of Guyana) tends to have a rainfall peak in December/January and again in June, which makes its bimodality slightly different from the rest of the region. Zone 5 (Lesser Antilles) tends to be almost unimodal with rainfall steadily rising and peaking in July/August. This is also reflected in the station data (see Table 3.2) for the countries falling within Zone 5. This may in part explain why when the region is averaged as a whole in this and other studies, the bi-modal pattern is sometimes not evident. The latter may also be in part a function of the averaging period used.
- Overall, the central Caribbean (Zones 3 and 4) receives smaller rainfall amounts ranging from approximately 2 to 17 mm/month while the far western and southern Caribbean (Zones 1 and 6) receive rainfall amounts ranging from approximately 2 to 27 mm/month.

Table 3.2 gives the mean monthly rainfall for stations in the individual countries. Data availability varies by country, and as such the periods used in calculating the climatologies are given in Table 3.1. The individual country climatologies pattern the climatological variations of the zones in which they fall, i.e. there is consistency between the timing of the peaks in rainfall and the driest periods.

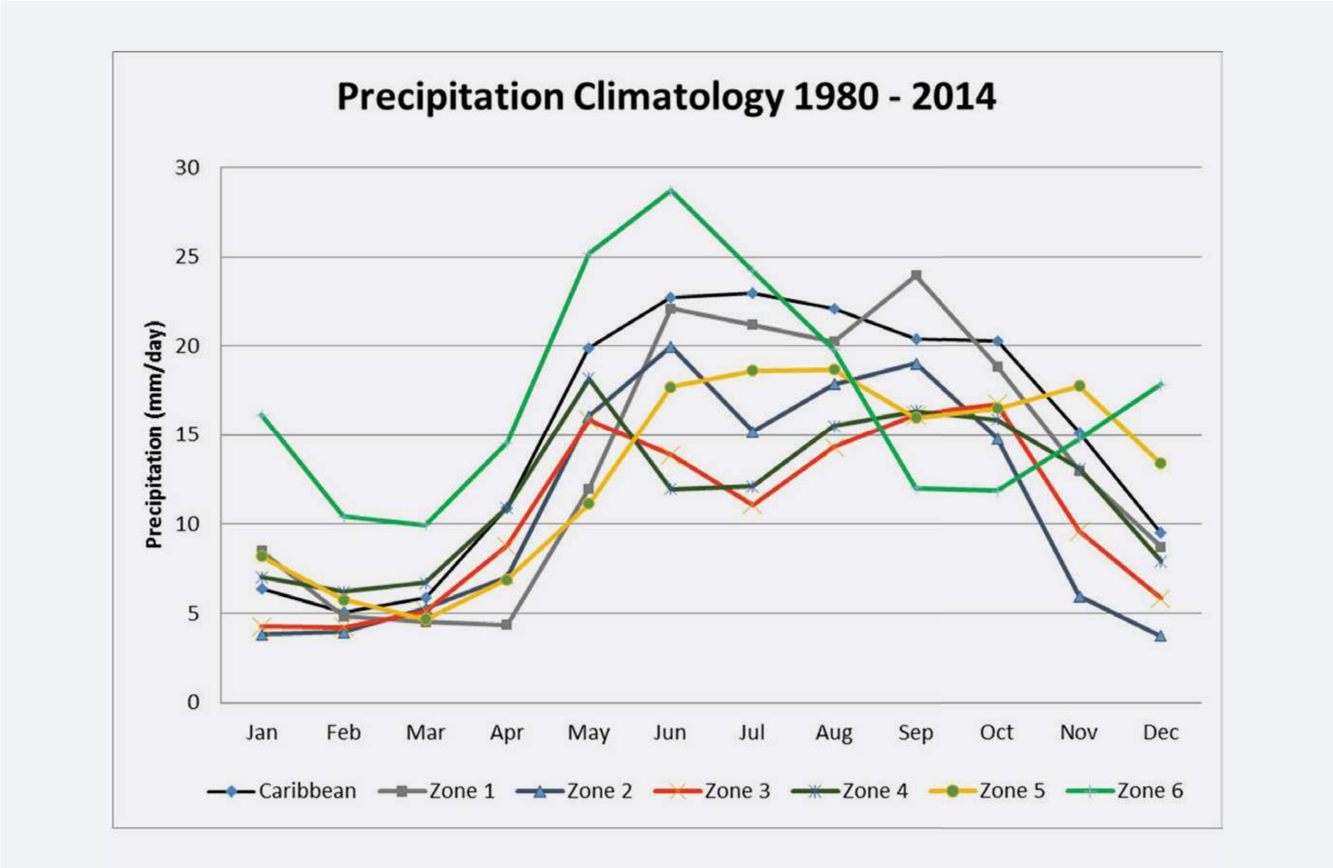



**Figure 3.2:** Climatological rainfall pattern (1980 to 2014) for the Caribbean and the six defined rainfall zones. Data source: UDel.

**Table 3.2:** Rainfall climatologies calculated from station data across selected Caribbean countries. Time periods used to calculate the means are indicated in column 3. Data source: CAROGEN.

| | | PRECIPITATION MONTHLY TOTAL CLIMATOLOGIES (MM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STATION | PERIOD | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
| **ANGUILLA** | | | | | | | | | | | | | |
| Metro | 1993 to 2017 | 49 | 31 | 44 | 44 | 69 | 47 | 66 | 80 | 98 | 121 | 92 | 78 |
| **ANTIGUA AND BARBUDA** | | | | | | | | | | | | | |
| VCB Airport | 1971 to 2017 | 46 | 38 | 37 | 60 | 62 | 49 | 63 | 88 | 113 | 135 | 116 | 83 |
| **BARBADOS** | | | | | | | | | | | | | |
| GA Airport | 1979 to 2017 | 68 | 38 | 38 | 46 | 40 | 87 | 101 | 147 | 110 | 162 | 140 | 89 |
| **BELIZE** | | | | | | | | | | | | | |
| Belmopan | 1979 to 2017 | 118 | 53 | 39 | 26 | 74 | 227 | 245 | 282 | 254 | 220 | 190 | 130 |
| **BRITISH VIRGIN ISLANDS** | | | | | | | | | | | | | |
| - | - | - | - | - | - | - | - | - | - | - | - | - | - |

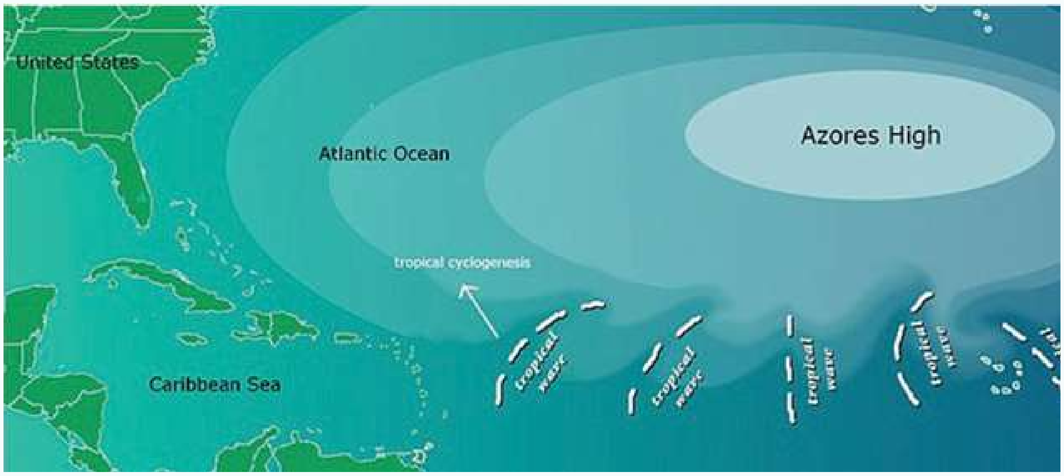
## PRECIPITATION MONTHLY TOTAL CLIMATOLOGIES (MM)

| STATION | PERIOD | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CAYMAN ISLANDS** | | | | | | | | | | | | | |
| Metro | 1971 to 2017 | 36 | 29 | 27 | 21 | 107 | 126 | 113 | 141 | 193 | 183 | 110 | 62 |
| **DOMINICA** | | | | | | | | | | | | | |
| Douglas-Charles | 1971 to 2017 | 129 | 90 | 104 | 121 | 192 | 159 | 207 | 242 | 271 | 313 | 293 | 189 |
| **GRENADA** | | | | | | | | | | | | | |
| Maurice Bishop | 1986 to 2017 | 50 | 28 | 21 | 16 | 29 | 121 | 110 | 144 | 119 | 125 | 162 | 82 |
| **GUYANA** | | | | | | | | | | | | | |
| Georgetown | 1971 to 2017 | 164 | 81 | 80 | 127 | 293 | 297 | 272 | 161 | 87 | 75 | 143 | 237 |
| **HAITI** | | | | | | | | | | | | | |
| Port-au-Prince | 1971 to 2017 | 30 | 36 | 84 | 130 | 152 | 117 | 60 | 94 | 107 | 130 | 67 | 17 |
| **JAMAICA** | | | | | | | | | | | | | |
| Norman Manley | 1971 to 2017 | 10 | 12 | 22 | 26 | 47 | 46 | 25 | 37 | 18 | 95 | 62 | 19 |
| **MONTSERRAT** | | | | | | | | | | | | | |
| - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| **ST KITTS AND NEVIS** | | | | | | | | | | | | | |
| Metro | 1972 to 2017 | 60 | 57 | 51 | 53 | 66 | 66 | 66 | 94 | 101 | 117 | 131 | 79 |
| **ST LUCIA** | | | | | | | | | | | | | |
| Hewanorra Airport | 1973 to 2017 | 72 | 49 | 48 | 48 | 56 | 98 | 145 | 165 | 157 | 159 | 165 | 99 |
| **ST VINCENT AND THE GRENADINES** | | | | | | | | | | | | | |
| ET Joshua Airport | 1979 to 2017 | 128 | 90 | 87 | 87 | 90 | 200 | 266 | 225 | 235 | 233 | 249 | 152 |
| **SURINAME** | | | | | | | | | | | | | |
| Cultuurtuin | 1971 to 2017 | 149 | 138 | 131 | 201 | 314 | 280 | 271 | 159 | 78 | 101 | 130 | 180 |
| **THE BAHAMAS** | | | | | | | | | | | | | |
| Lynden Pindling | 1971 to 2017 | 35 | 40 | 36 | 48 | 109 | 192 | 162 | 211 | 167 | 147 | 55 | 23 |
| **TRINIDAD AND TOBAGO** | | | | | | | | | | | | | |
| Piarco Airport | 1971 to 2017 | 65 | 41 | 28 | 32 | 87 | 245 | 238 | 255 | 190 | 216 | 209 | 157 |
| **TURKS AND CAICOS ISLANDS** | | | | | | | | | | | | | |
| - | - | - | - | - | - | - | - | - | - | - | - | - | - |

Box 3.1 provides a brief synthesis of some of the large-scale dynamical features that give rise to the mean Caribbean rainfall pattern.

INFORMATION BOX 3.1

## WHAT DETERMINES WHEN THE CARIBBEAN IS WET AND DRY?




An interplay between a number of large-scale climatic features gives rise to the annual climatology of the Caribbean. For example, one of the important large-scale features that strongly modulates the Caribbean rainfall climatology is the semi-permanent subtropical anticyclone known as the North Atlantic Subtropical High (NASH) or Azores High. Variations in the intensity of the Azores High due to its annual northward trek during the warmer summer months significantly impact the strengths of the easterly trade winds as well as subsidence across the Caribbean region. The influence of the Azores High is strongest during the Caribbean dry season and again briefly during July/August (coincident with the mid-summer drought) generally bringing dry conditions. Variations in the NASH, then, roughly define the dry and wet seasons in the Caribbean.

A second important feature which helps define the rainfall seasons across the Caribbean is the Atlantic Warm Pool (AWP) (see Section 3.3.1). The AWP appears in boreal spring in the far northwestern Caribbean, thereafter expanding across the Caribbean Sea through to August-September before contracting and disappearing by the end of the year. The appearance, peak and disappearance of the AWP roughly coincide with diminishing influence of the NASH, thereby helping to define the Caribbean rainfall season. A third feature of importance is the Inter-Tropical Convergence Zone (ITCZ). Its two branches in the Atlantic and the Eastern Pacific ITCZ have a seasonal migration which lags the north-south movement of maximum solar radiation. At their northernmost and southernmost extents, the branches influence rainfall amounts, particularly in the southern and western Caribbean mainland territories. In general, the seasonal changes in the NASH, AWP and ITCZ broadly account for the rainfall climatology in the Caribbean through their influence on the strength of the trades, the warmth of the SSTs, and subsidence.

Other regional influences which modulate sub-regional patterns include: (i) the Caribbean Low-Level Jet (CLLJ) which strongly influences the mid-summer drought (MSD); (ii) African Easterly Waves which traverse the Atlantic Basin from mid-June to early October and account for more than half of all Atlantic hurricanes and major hurricanes; (iii) the passage of north American cold fronts over the Northern Caribbean, particularly during the Caribbean dry season; and (iv) localized mechanisms such as sea breezes due to strong easterly winds induced by the NASH, which together with orographic lifting result in rainfall on the leeward side of Caribbean islands and the Caribbean coast of Central America.

A number of studies provide an overview of the interplay of all the above mechanisms including Giannini et al. 2000; Taylor and Alfaro 2005; Wang and Lee 2007; Maldonado et al. 2018; and Martinez et al. 2019.

### 3.2.2. RAINFALL TIME SCALE DECOMPOSITION AND TRENDS

Figure 3.3 shows monthly rainfall amounts for the Caribbean region for the period 1900 - 2014. The figure depicts a slight downward trend in rainfall which is, however, not statistically significant. There is a significant decadal variability (groups of years which are wet versus groups of years that are dry e.g. the 1940s and 1950s versus the 1960s and 1970s respectively), as well as (and even more so) significant interannual (year-to-year) variability. These results mirror the findings of Jones et al. (2015), which also provide an extensive analysis of long-term trends in Caribbean rainfall. Jones et al. (2015) note that annual and decadal variability appear to be the dominating influences in the Caribbean rainfall time series.

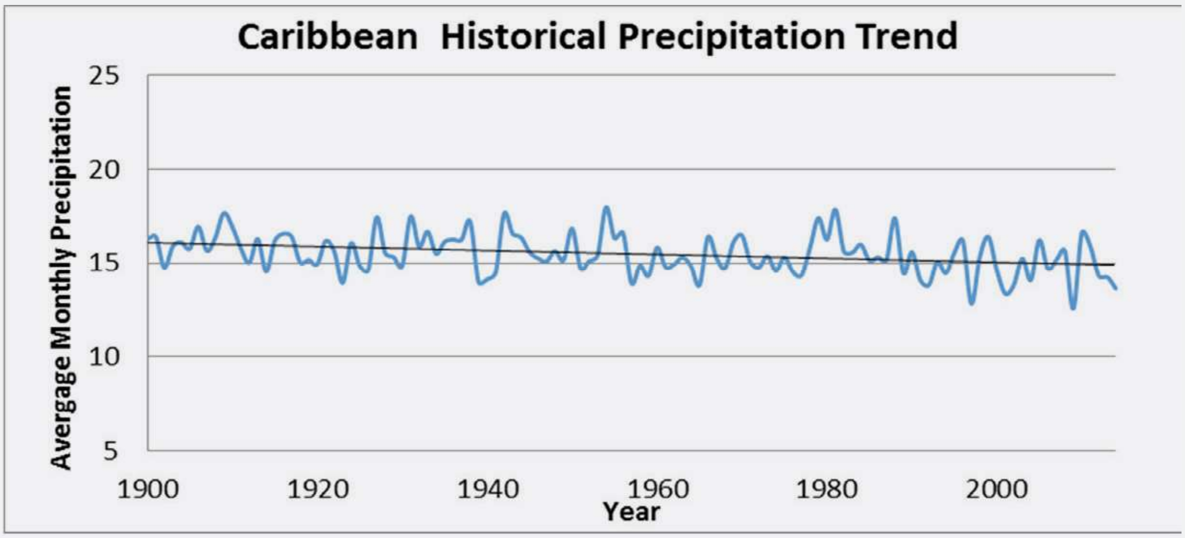



**Figure 3.3**: Historical Rainfall Trends (1900 to 2014) for the Caribbean. Source data: UDel.

Figure 3.4 shows the decomposition of the Caribbean region's rainfall anomaly time series for the twentieth century[7], that is, the rainfall record is broken down to show the relative contributions over time of the long term linear trend versus decadal and interannual variations. The figure shows the extracted patterns of variability and the statistics describing their relative contribution. Figure 3.4 confirms the previously noted conclusions about interannual and decadal variability being the dominant timescale of variability in the Caribbean rainfall record. The following are also noted:

- In the long term record, the Caribbean is not getting wetter or drier. The linear trend accounts for 0% in the observed variability and is not significant at the 5% significance level.
- Decadal variations account for 7% of the observed variability.
- Year-to-year (interannual) variations account for 91% of the observed rainfall pattern.

7 The Figure was created using the IRI Climate and Society Map Room Tool available at http://iridl.ldeo.columbia.edu/maproom.

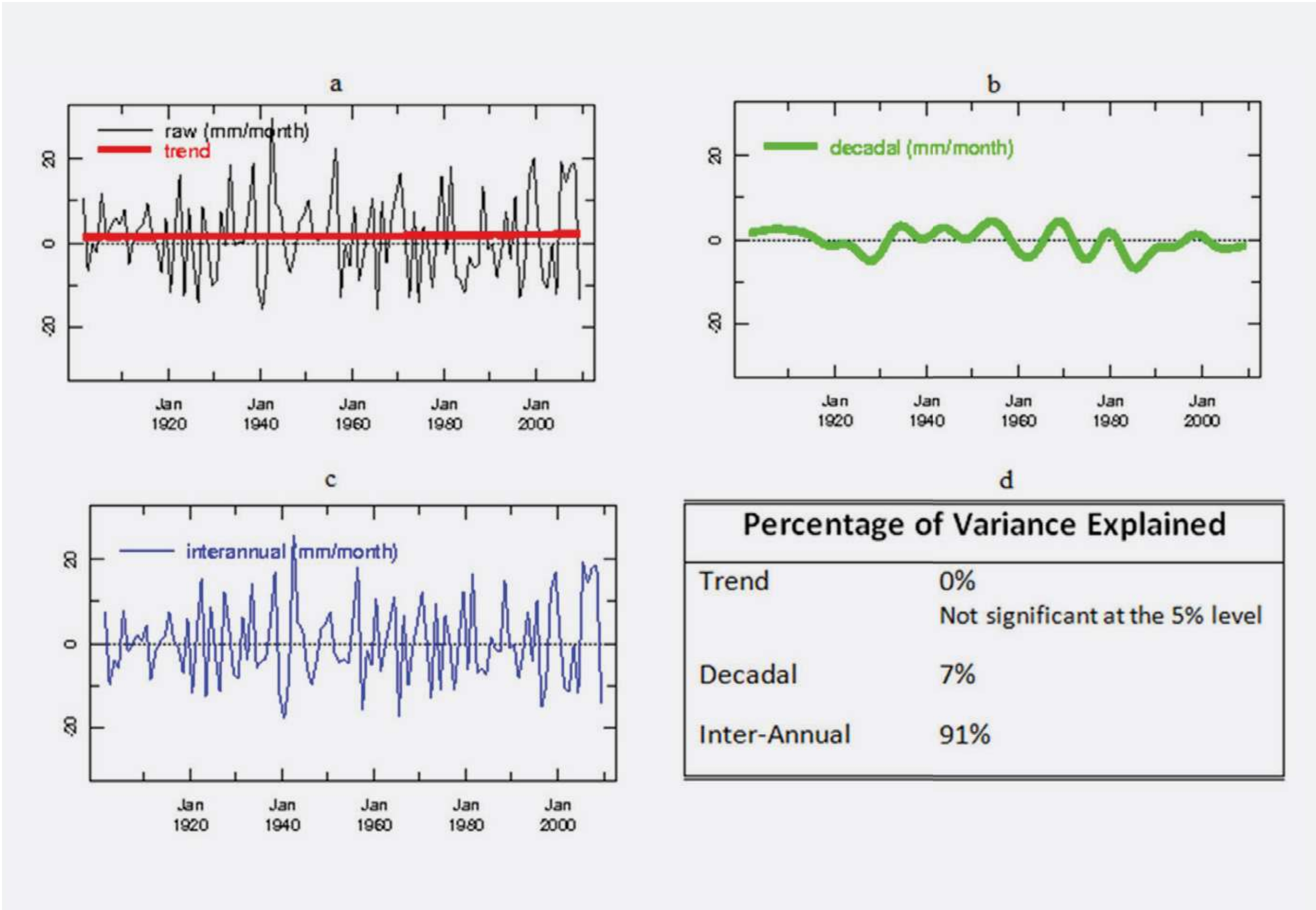



**Figure 3.4:** Historical Rainfall Anomaly Time Scales Decomposition for the Caribbean as a whole. Images generated using IRI Climate and Society Map Room Tool. Source rainfall data: CRU.

Figure 3.5 presents similar plots to that of Figure 3.3, but for the six rainfall zones. Zones 1-4 show slight downward trends, while Zones 5 and 6 show no appreciable trend. For four of the six zones the linear trends were statistically not significant. As was also true for the Caribbean-wide index, the patterns for each zone show decadal and interannual variability as the dominant influences in the time series. When the decomposition of the time series for each zone is done (Table 3.3), it is noted that:

- Linear trends account for 0% to 7% of the variability across all zones and are insignificant at the 5% confidence level except for Zone 5.
- Decadal signals account for 7% to 16% of the variability.
- 64% to 91% of the rainfall patterns are as a result of inter-annual variations.

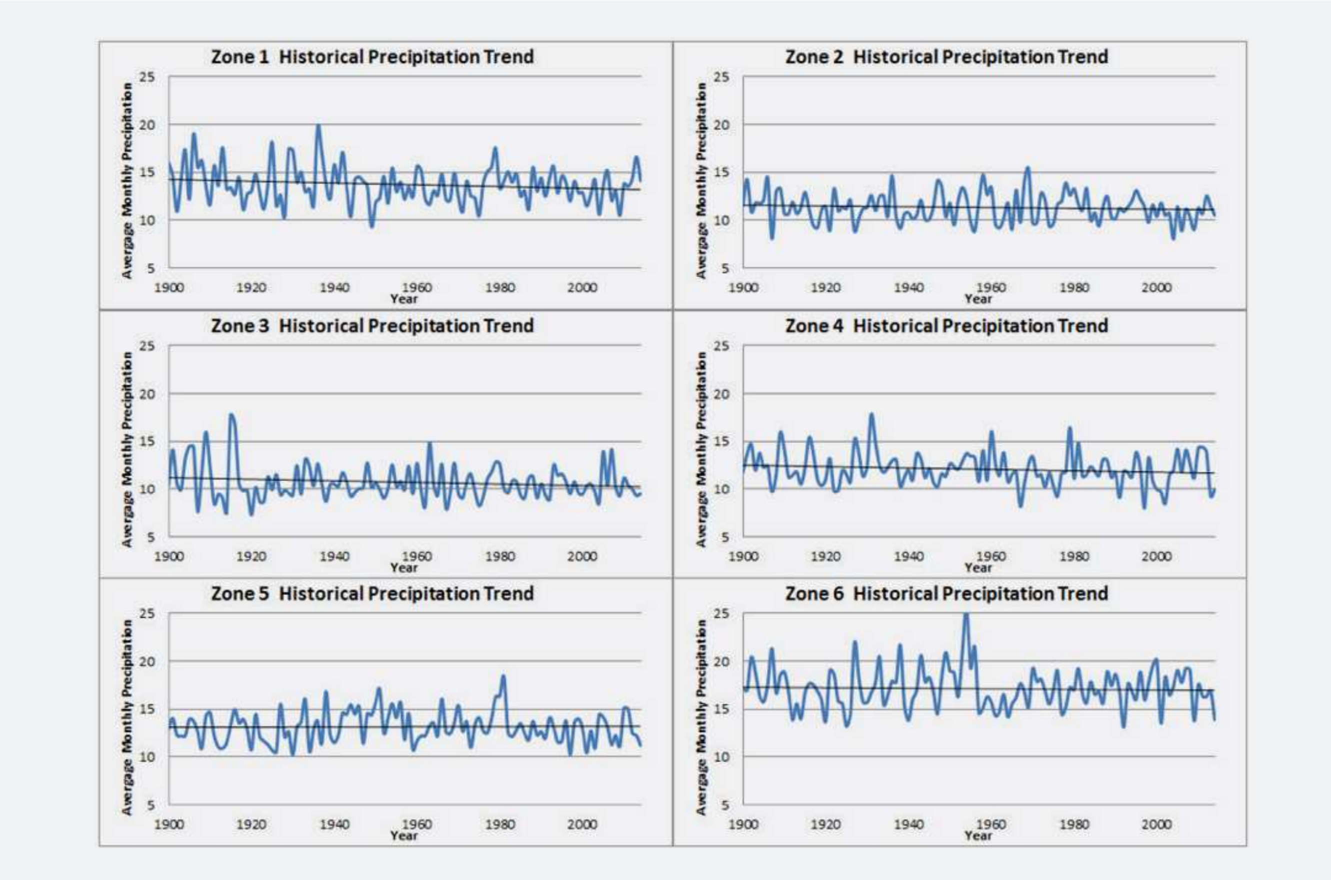



**Figure 3.5:** Historical Precipitation Trends (1900 to 2014) for the six defined rainfall zones.

**Table 3.3:** Precipitation Time Series Decomposition Numbers

| REGION | PERCENTAGE OF PRECIPITATION VARIANCE EXPLAINED | | |
|---|---|---|---|
| | TREND | DECADAL | INTER-ANNUAL |
| CARIBBEAN | 0%<br>Not significant at the 5% level | 7% | 91% |
| ZONE 1 | 0%<br>Not significant at the 5% level | 15% | 83% |
| ZONE 2 | 1%<br>Not significant at the 5% level | 12% | 81% |
| ZONE 3 | 1%<br>Not significant at the 5% level | 8% | 82% |
| ZONE 4 | 0%<br>Not significant at the 5% level | 10% | 80% |
| ZONE 5 | **7%**<br>**Significant at the 5% level** | 16% | 64% |
| ZONE 6 | 3%<br>Not significant at the 5% level | 10% | 79% |

### 3.2.3. RAINFALL EXTREMES AND TRENDS

Extreme indices are often used to provide more information about the mean climate of the region. Figure 3.6 gives the annual average for four common rainfall extreme indices derived for, and averaged over, the period 1980-2011: (i) Maximum Number of Consecutive Dry Days (CDD) (ii) Rainfall Amount on Very Wet Days i.e. when total rainfall exceeded the 95th percentile (R95p), (iii) Monthly Maximum One Day Rainfall Amount (RX1), and (iv) Monthly Maximum Consecutive Five Day Rainfall Amount (RX5). The plots are derived for the stations listed in Table 3.2.

Over the period under analysis, CDD fell in the range 10 to 32 days. Countries located in Zones 1 and 3 seem to exhibit largest CDD, with Belize Central Farm having the highest number of consecutive dry days. The southern Caribbean countries, those in Zone 6, had lowest CDD values. Zones 1 and 3 had the highest values for the extreme rainfall indices (i.e. RX1 and RX5). Melville Hall, Dominica recorded the highest values for the heavy rainfall indices i.e. R95p (864 mm), RX1 (152 mm) and RX5 (285 mm) and the lowest value for CDD (10 days).

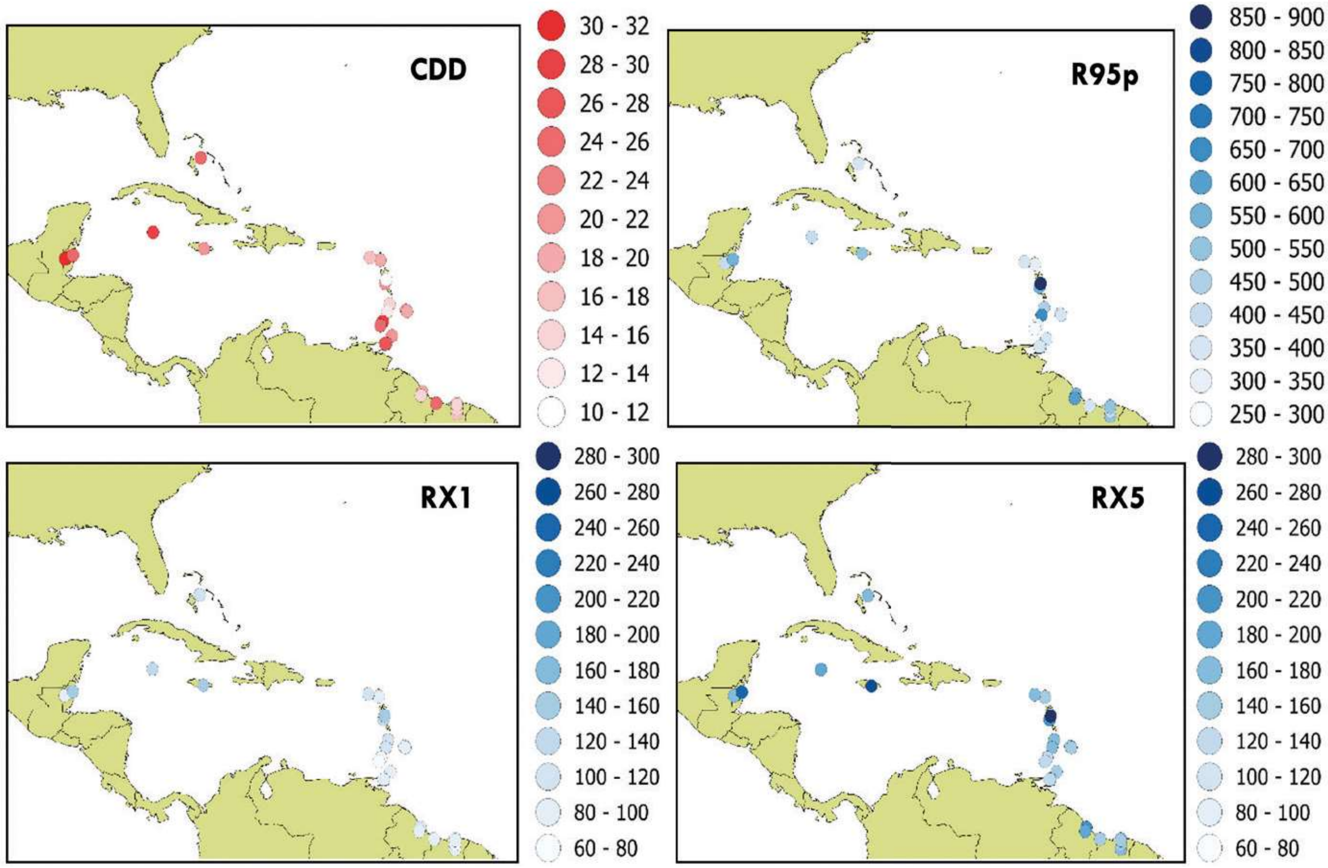



**Figure 3.6:** Top row: Maximum Number of Consecutive Dry Days (CDD) and Rainfall Amount for Very Wet Days (R95p). Bottom row: Monthly Maximum One Day Rainfall Amount and Monthly Maximum Consecutive Five Day Rainfall Amount (RX5) for the Caribbean region over the period 1980 to 2011. Units are days for CDD and mm for R95p, RX1 and RX5. Data source: CAROGEN.

Table 3.4 gives the slope estimates for the extreme rainfall indices over the period 1980 to 2011. The Caribbean on average showed an increasing trend for all four extreme rainfall indices i.e., the number of consecutive dry days between rainfall events are increasing, as well as the amount of rainfall that falls during rainfall events. When analysed by zones i.e. averaging the station values that fell in a zone, Zone 3 showed an increasing trend for all four extreme rainfall indices, while R95p was increasing for all zones. CDD increased for Zones 1, 3 and 5, however the increase was negligible. Zone 6 showed a decrease in CDD. None of the studied countries fell in Zones 2 and 4.

**Table 3.4:** Slope Estimates for Extreme Rainfall Indices (1980 to 2011)

| REGION | CDD | R95P | RX1 | RX5 |
|---|---|---|---|---|
| CARIBBEAN | 0.024 | 3.372 | 0.094 | 0.675 |
| ZONE 1 | 0.073 | 0.224 | -0.506 | -0.309 |
| ZONE 2 | - | - | - | - |
| ZONE 3 | 0.070 | 5.467 | 0.583 | 3.073 |
| ZONE 4 | - | - | - | - |
| ZONE 5 | 0.075 | 1.537 | 0.016 | -0.068 |
| ZONE 6 | -0.109 | 6.357 | -0.066 | -0.700 |

## 3.3. TEMPERATURE (SEA SURFACE & AIR)

In this section, sea surface temperature (SST) and near-surface air temperature plots are presented for the region. For SST, a bi-monthly spatial pattern is presented in addition to the spatial long-term trend. For air-temperature, the climatologies of the Caribbean region and the six defined rainfall zones are presented. The section also presents a decomposition of the historical time series of air-temperature as well as an examination of temperature extremes.

The SST dataset utilised is the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation (OI) SST V2 High Resolution dataset (Reynolds et al. 2002). The UDel dataset (Willmott et al. 2001) is utilised for air-temperature climatologies and time series trends, while time scale decomposition of the historical air-temperature data was done utilising the International Research Institute (IRI) Climate and Society Map Room Tool (Greene et al. 2011). As previously noted, the IRI tool utilises the Climate Research Unit (CRU) dataset ((Harris et al. 2014)). Station data for individual countries are obtained from the CAROGEN portal. (See again Chapter 2 for a description of all datasets.)

### 3.3.1. SEA SURFACE TEMPERATURE CLIMATOLOGY AND TRENDS

Figure 3.7 presents mean SST maps for the wider tropical Atlantic, including the Caribbean, for selected months. The appearance, expansion and decline of the Atlantic Warm Pool (AWP) and how it modulates Caribbean basin SSTs are evident in the plots. At the start of the year and during the northern hemisphere winter season, the Caribbean is relatively cool with SSTs of 27°C and below. SSTs gradually increase, with warmer waters first appearing in the western Caribbean (the Gulf of Mexico) and then spreading eastward, eventually reaching the tropical Atlantic coast of the African continent during the summer months. SSTs exceed 29°C across the Gulf of Mexico and the Caribbean basin during summer (peaking in August), with SSTs greater than 27.5°C extending through to the east Coast of Africa. The pattern reverses thereafter, as SSTs gradually cool and the AWP disappears by the onset of the winter months. It is, therefore, to be noted that warm waters greater than the 27.5°C convection threshold exist over much of the north tropical Atlantic during the summer and late rainfall season. This makes for extremely conducive conditions along the path traversed by tropical easterly waves and facilitate their development into tropical storms and hurricanes.

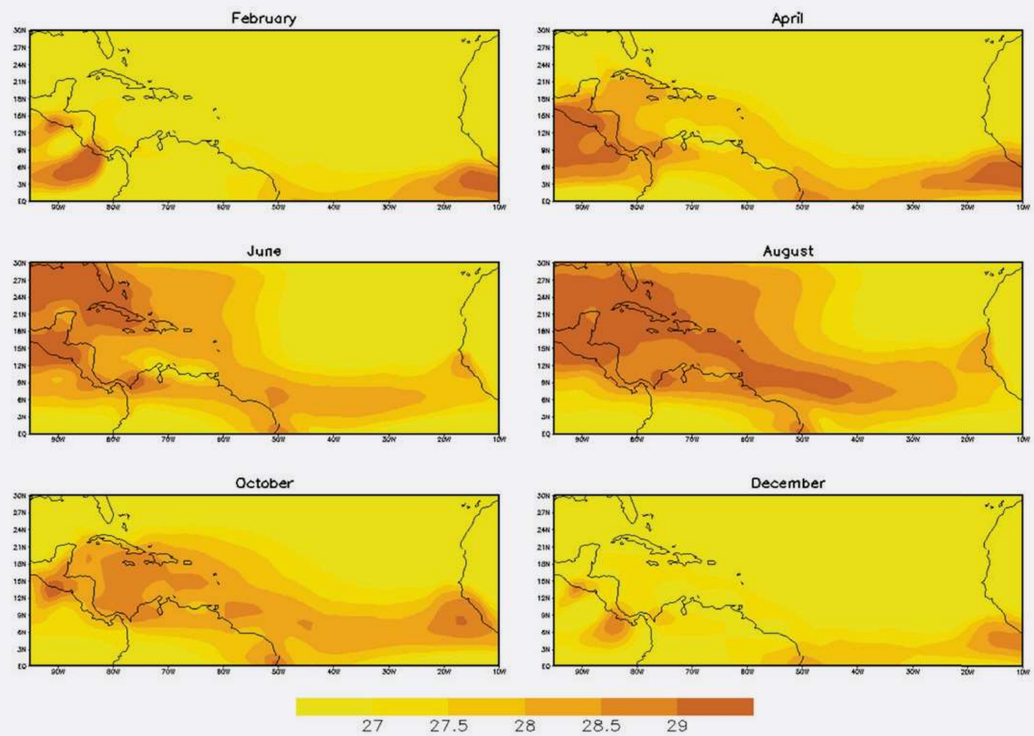



**Figure 3.7:** Climatology (1982 – 2016) of Sea Surface Temperature (SST) for the Caribbean region and Tropical North Atlantic (TNA). Dataset: NOAA-OI.

Figure 3.8 depicts average SST values for the Caribbean region as a whole and for each of the six defined rainfall zones. SST is coolest in December/January (winter) for all six defined zones, ranging from 25°C to 26.8°C, and warmest in July/August (summer) ranging from 28.6°C to 29.6°C. Except for Zone 2, all other zones and the Caribbean as a whole exhibit a highly correlated SST pattern. The difference shown by Zone 2 can be attributed to its far north location which accounts for a wider extent in its temperature range.

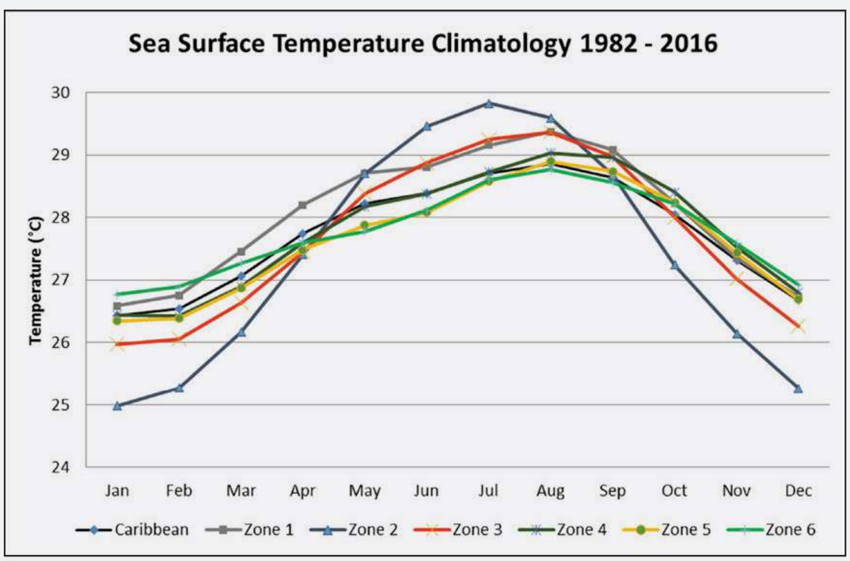



**Figure 3.8:** Climatology (1982 to 2016) Sea Surface Temperature (SST) for the Caribbean and the six defined rainfall zones. Dataset: NOAA-OI.

Figure 3.9 presents the trend in SSTs for the Caribbean region and surrounding area. Over the period 1982-2016, it shows that SSTs have warmed at a rate of between 0.01°C and 0.04°C annually. Higher rates of warming can be observed in the Gulf of Mexico and the eastern Caribbean extending into the eastern tropical Atlantic. Cooling is only observed in the far northern edge of the domain, in the vicinity of Florida.

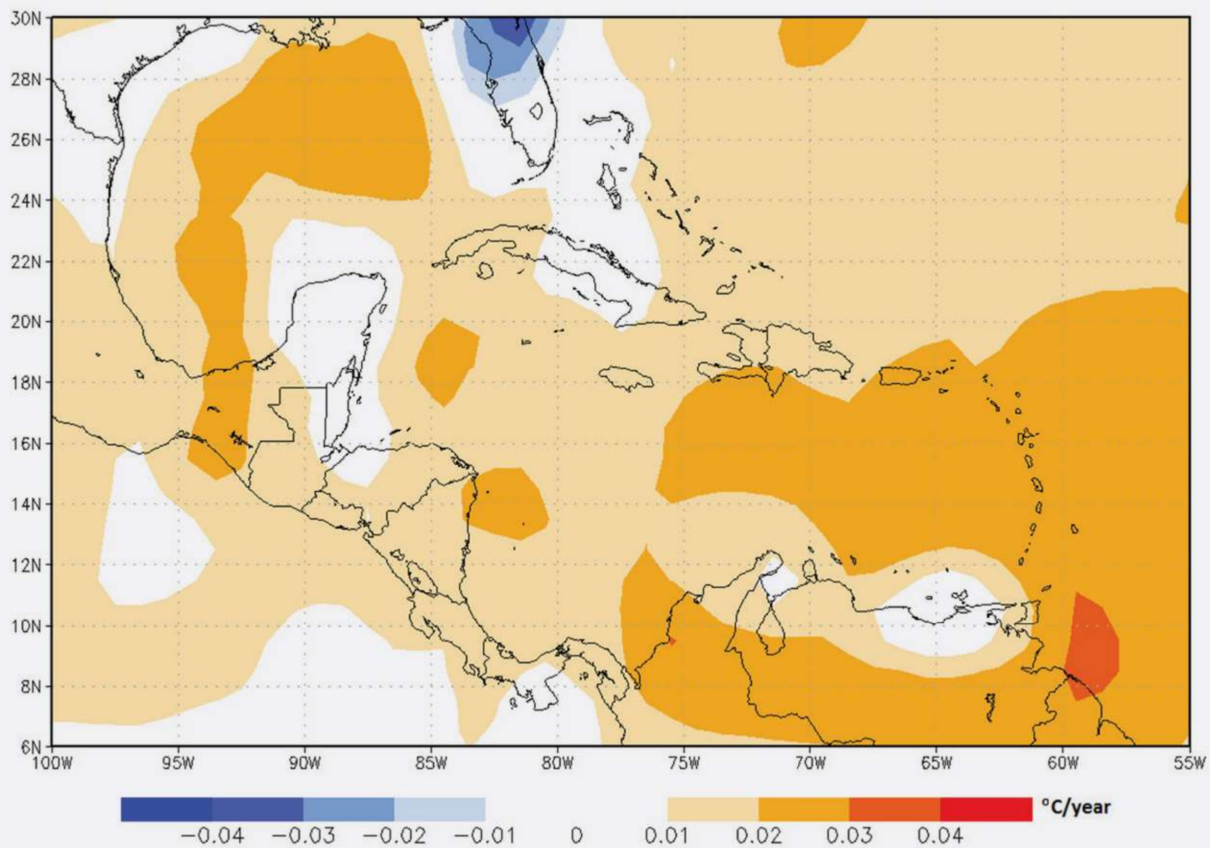



**Figure 3.9:** Map showing sea surface temperature trends within the Caribbean and surrounding regions over the period 1982 to 2016.

### 3.3.2. AIR TEMPERATURE CLIMATOLOGY

Figure 3.10 presents the climatologies of air temperature for the Caribbean and the six defined zones. It shows that the average monthly air-temperature in the region generally ranges from approximately 22°C to 28°C throughout the course of the year. Coolest temperatures occur during the winter months for the Caribbean as a whole and across the region, while warmest temperatures generally occur in the summer months, peaking in August. Zones 1 and 6, however, have temperatures peaking in May and September respectively, likely reflecting the respective influences of the Pacific and Atlantic ITCZ. The south-eastern Caribbean (Zone 6), experience slightly lower temperatures than the western Caribbean (Zones 1 to 3).

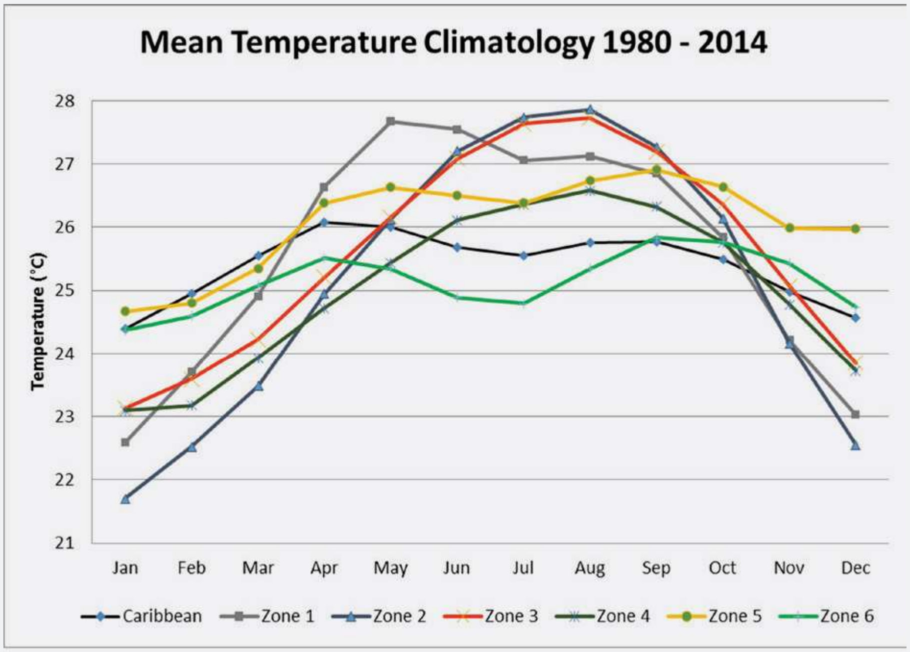



**Figure 3.10:** Climatological air temperature pattern (1980 to 2014) for the Caribbean as a whole and its six defined rainfall zones.

Table 3.5 presents air-temperature climatologies for individual countries. As noted for the rainfall, the temperature climatologies calculated using the station data mirror the patterns for the zones in which the stations fall.

Table 3.5: Temperature climatologies calculated from station data across selected Caribbean countries. Time periods used to calculate the means are indicated in column 3. Data source: CAROGEN.

| | | PRECIPITATION MONTHLY TOTAL CLIMATOLOGIES (MM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STATION | PERIOD | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
| **ANGUILLA** | | | | | | | | | | | | | |
| - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| **ANTIGUA AND BARBUDA** | | | | | | | | | | | | | |
| VCB Airport | 1971 to 2017 | 25.3 | 25.3 | 25.6 | 26.3 | 27.0 | 27.8 | 28.0 | 28.2 | 28.0 | 27.4 | 26.7 | 25.8 |
| **BARBADOS** | | | | | | | | | | | | | |
| GA Airport | 1979 to 2017 | 25.8 | 25.9 | 26.1 | 26.8 | 27.6 | 27.7 | 27.7 | 27.9 | 27.8 | 27.5 | 27.2 | 26.5 |
| **BELIZE** | | | | | | | | | | | | | |
| Belmopan | 1979 to 2017 | 23.6 | 24.1 | 25.1 | 27.0 | 28.3 | 28.1 | 27.5 | 27.6 | 27.6 | 26.5 | 24.8 | 23.8 |
| **BRITISH VIRGIN ISLANDS** | | | | | | | | | | | | | |
| - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| **CAYMAN ISLANDS** | | | | | | | | | | | | | |
| Metro | 1971 to 2017 | 25.6 | 25.5 | 26.1 | 27.4 | 28.1 | 28.9 | 29.3 | 29.3 | 29.0 | 28.1 | 27.3 | 26.2 |
| **DOMINICA** | | | | | | | | | | | | | |
| Douglas-Charles | 1981 to 2017 | 25.4 | 25.1 | 25.2 | 26.1 | 26.9 | 27.7 | 27.7 | 27.8 | 27.6 | 27.2 | 26.5 | 25.8 |
| **GRENADA** | | | | | | | | | | | | | |

| | | PRECIPITATION MONTHLY TOTAL CLIMATOLOGIES (MM) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| STATION | PERIOD | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
| Maurice Bishop | 1985 to 2017 | 26.4 | 26.5 | 26.9 | 27.6 | 28.1 | 27.8 | 27.6 | 27.9 | 28.2 | 27.9 | 27.5 | 27.0 |
| **GUYANA** | | | | | | | | | | | | | |
| Georgetown | 1971 to 2017 | 26.4 | 26.7 | 26.9 | 27.2 | 27.1 | 26.9 | 26.9 | 27.3 | 27.9 | 28.0 | 27.6 | 26.7 |
| **HAITI** | | | | | | | | | | | | | |
| Port-au-Prince | 2000 to 2017 | 26.7 | 27.0 | 27.4 | 28.3 | 28.8 | 30.6 | 30.8 | 30.6 | 29.6 | 29.2 | 28.2 | 27.5 |
| **JAMAICA** | | | | | | | | | | | | | |
| Sangster Airport | 1973 to 2017 | 25.7 | 25.5 | 26.3 | 27.1 | 27.5 | 28.2 | 28.7 | 28.8 | 28.3 | 27.9 | 27.1 | 26.1 |
| **MONTSERRAT** | | | | | | | | | | | | | |
| - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| **ST KITTS AND NEVIS** | | | | | | | | | | | | | |
| Nat-Agric-Station | 1972 to 2015 | 25.6 | 25.4 | 25.9 | 26.6 | 27.3 | 28.1 | 28.3 | 28.5 | 28.3 | 27.9 | 27.1 | 26.2 |
| **ST LUCIA** | | | | | | | | | | | | | |
| Hewanorra Airport | 1979 to 2017 | 26.4 | 26.3 | 26.8 | 27.4 | 28.2 | 28.2 | 28.2 | 28.3 | 28.3 | 28.1 | 27.7 | 27.5 |
| **ST VINCENT AND THE GRENADINES** | | | | | | | | | | | | | |
| ET Joshua Airport | 1979 to 2017 | 25.6 | 25.6 | 25.9 | 26.8 | 27.4 | 27.4 | 27.4 | 27.5 | 27.7 | 27.4 | 27.0 | 26.4 |
| **SURINAME** | | | | | | | | | | | | | |
| Cultuurtuin | 1971 to 2017 | 26.7 | 26.7 | 27.1 | 27.3 | 27.1 | 27.2 | 27.4 | 28.0 | 28.4 | 28.4 | 27.8 | 26.9 |
| **THE BAHAMAS** | | | | | | | | | | | | | |
| Lynden Pindling | 1971 to 2017 | 20.4 | 20.9 | 21.1 | 23.6 | 25.3 | 26.9 | 27.5 | 27.6 | 27.4 | 25.9 | 23.3 | 21.3 |
| **TRINIDAD AND TOBAGO** | | | | | | | | | | | | | |
| Piarco Airport | 1971 to 2017 | 25.4 | 25.6 | 26.2 | 27.0 | 27.3 | 26.9 | 26.8 | 26.9 | 27.0 | 26.8 | 26.4 | 25.8 |
| **TURKS AND CAICOS ISLANDS** | | | | | | | | | | | | | |
| - | - | - | - | - | - | - | - | - | - | - | - | - | - |

### 3.3.3. AIR-TEMPERATURE TIME SCALE DECOMPOSITION AND TRENDS

Figure 3.11 gives a plot of the historical (1900 to 2014) air-temperature for the Caribbean region. It shows a strong linear trend of approximately 0.09oC/decade which is statistically significant. This is in contrast to the Caribbean rainfall record (see again Section 3.2). The strong linear trend in the Caribbean temperature record is consistent with other studies which have similarly noted a dominant linear trend in the temperature records of the region (see for example Jones et al. 2014; Stephenson et al. 2012). The increase is also consistent with the global warming trend recorded over the past century (IPCC 2018). Stephenson et al. (2014) also show an increase in the Caribbean average day time (nighttime) temperature of approximately 0.19 °C/decade (0.28°C/decade) over the period 1960-2010. The difference between the rates of increase of day versus nighttime temperatures further suggests a decrease in the diurnal temperature range. Figure 3.11 also illustrates the annual and decadal variability evident in the Caribbean historical temperature record.

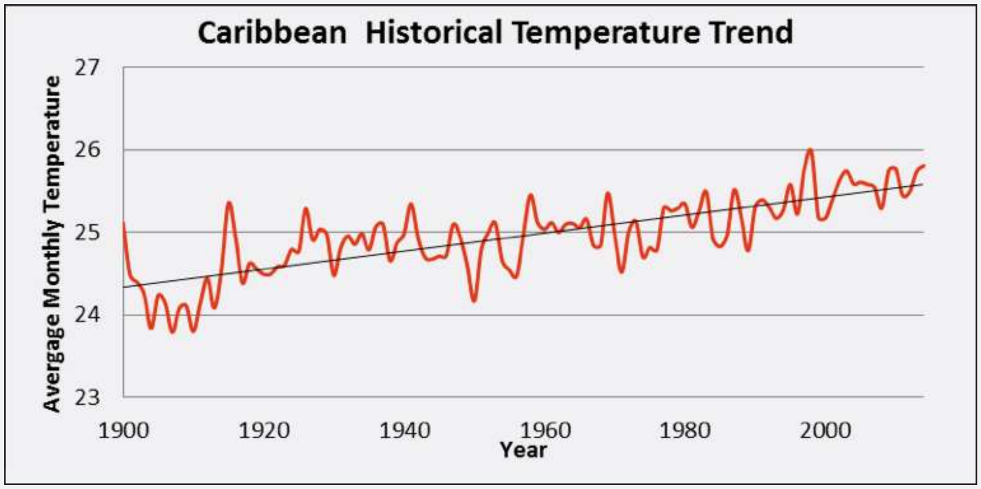



**Figure 3.11:** Historical Temperature (°C) Trends (1900 to 2014) for the Caribbean as a whole. Data Source: CRU.

Similar to Figure 3.4, Figure 3.12 shows a decomposition of the Caribbean region's air-temperature anomaly time series for the twentieth century. The linear trend accounts for 65% in the observed change in temperature and is significant at the 1% significance level. In comparison, the decadal signal accounts for 9%, while interannual variations account for 24% of the observed signal's pattern.

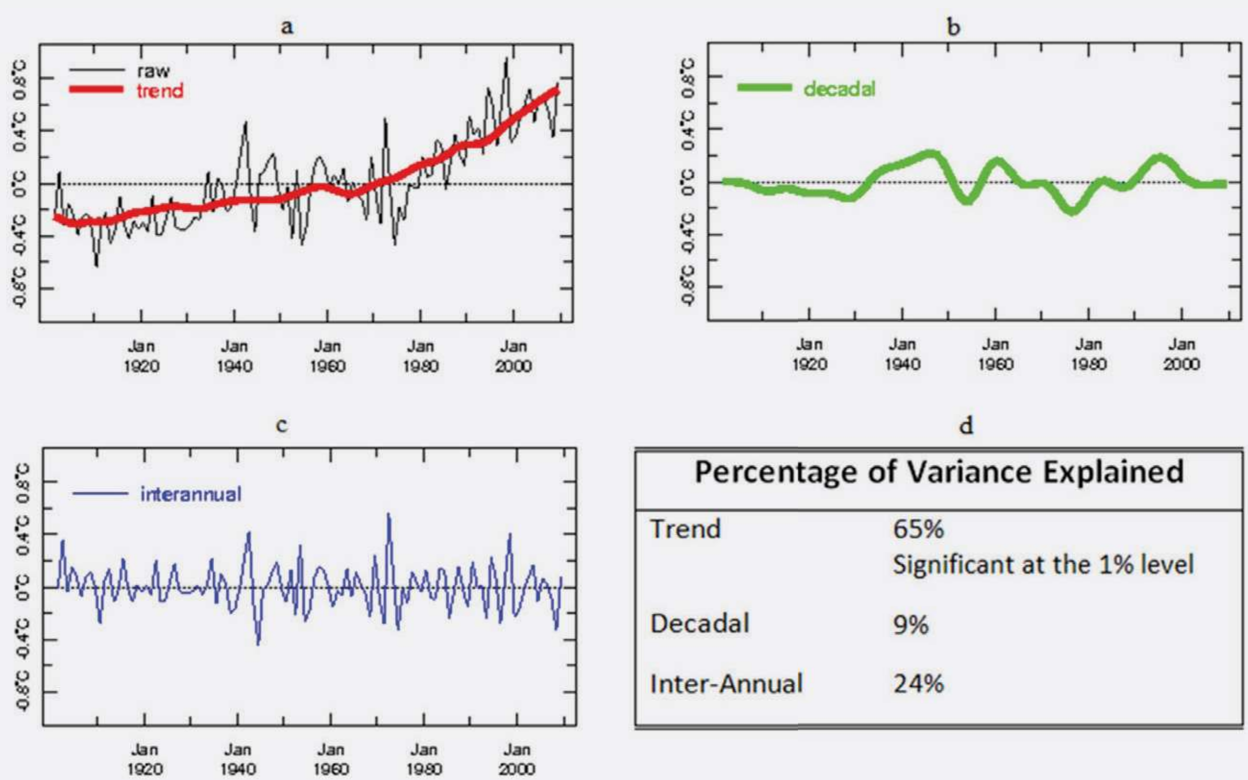



Figure 3.12: Historical Temperature Time Scales for the Caribbean. Images generated using IRI Maproom (https://iridl.ldeo.columbia.edu/maproom/Global/Time_Scales/). Data Source: CRU.

Figure 3.13 presents a similar plot to Figure 3.11, but for the historical air-temperature of the region's six defined rainfall zones. All except Zone 2 display a significant upward linear trend, along with annual and decadal variability. Table 3.6 presents the numerical values for the decomposed time series. The following things are noted:

- Linear trends accounts for 17% to 65% of the variability and are all significant at the 1% confidence
- Decadal signals account for 9% to 22% of the variability.
- 22% to 56% of the signals pattern is as a result of inter-annual variations.

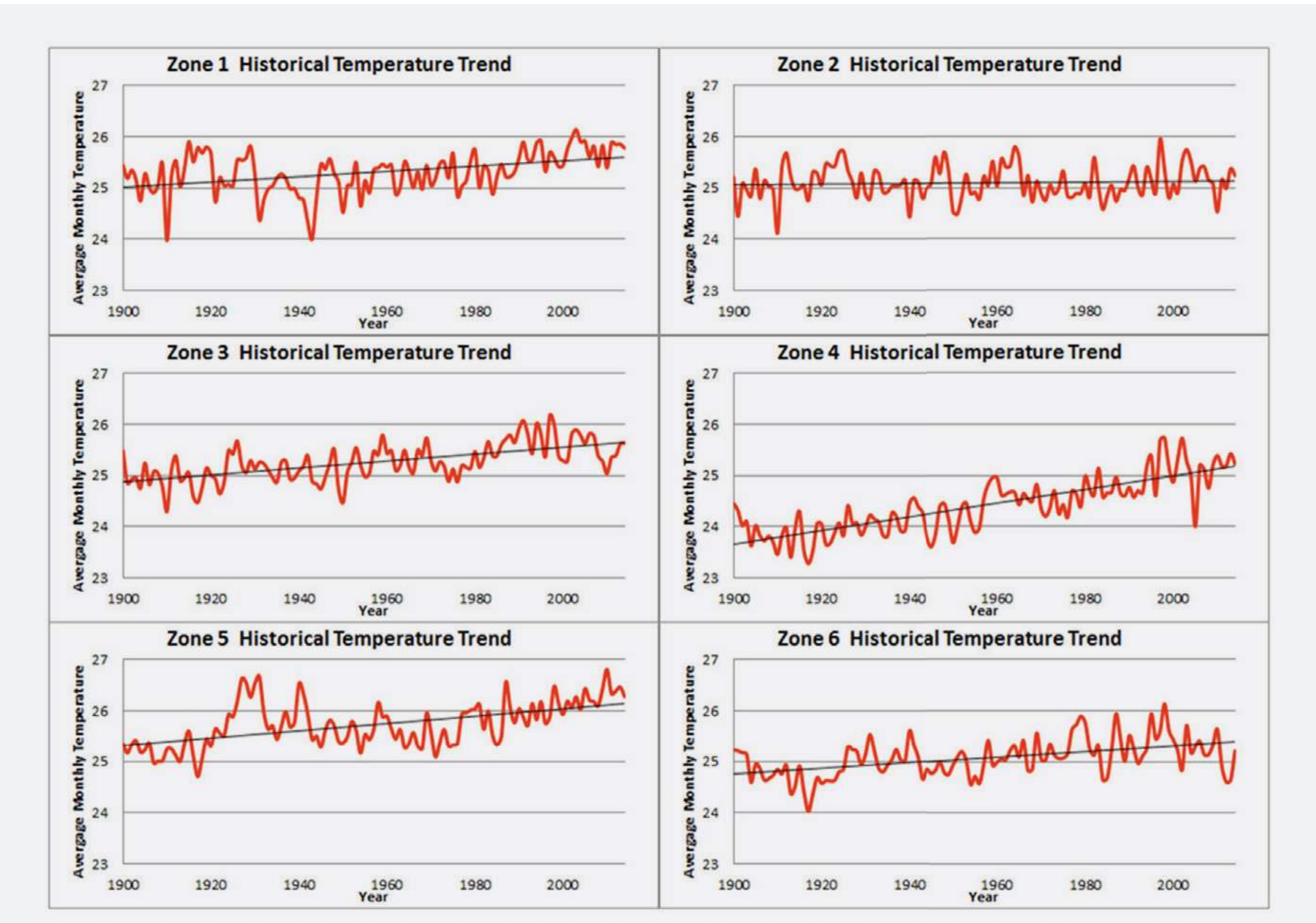


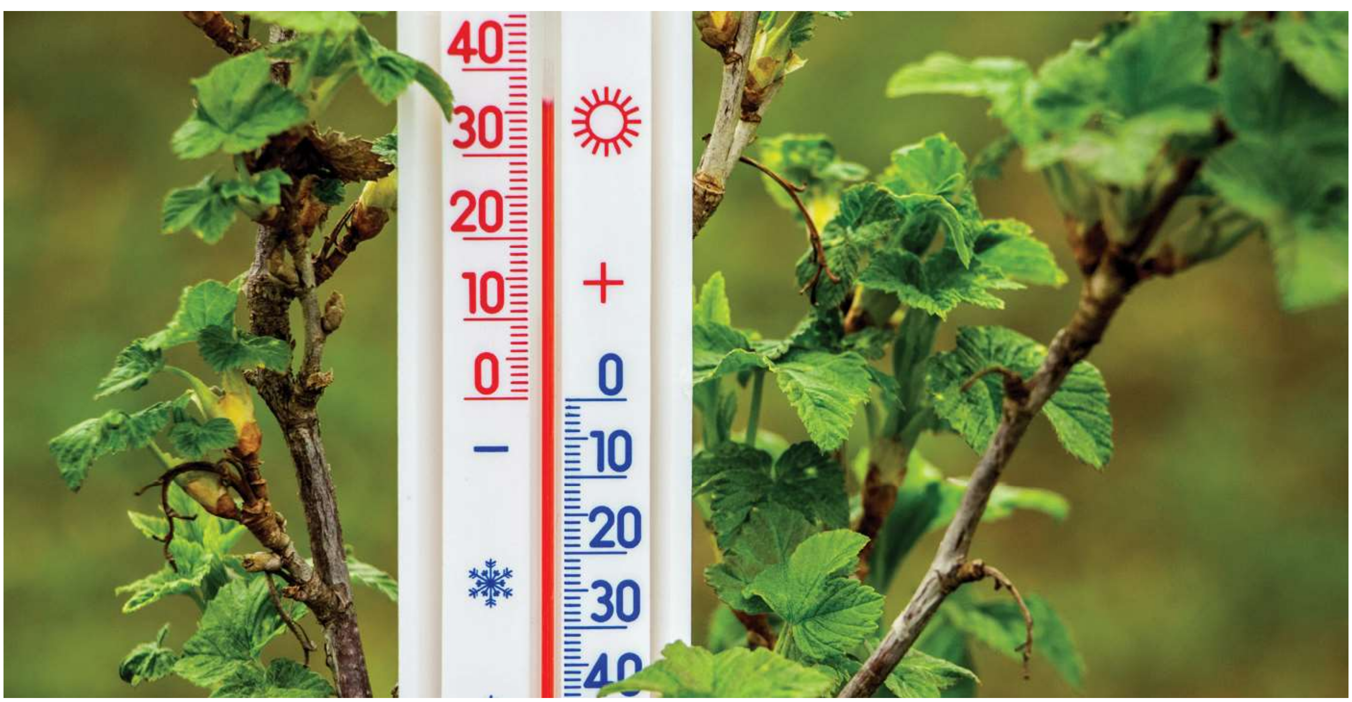

**Figure 3.13:** Historical Air-Temperature Trends (1900 to 2014) for the Caribbean six rainfall zones.

**Table 3.6:** Air-Temperature Time Series Decomposition Numbers

| REGION | PERCENTAGE OF TEMPERATURE VARIANCE EXPLAINED | | |
|---|---|---|---|
| | TREND | DECADAL | INTER-ANNUAL |
| CARIBBEAN | 65%<br>Significant at the 1% level | 9% | 24% |
| ZONE 1 | 38%<br>Significant at the 1% level | 18% | 41% |
| ZONE 2 | 17%<br>Significant at the 1% level | 18% | 56% |
| ZONE 3 | 45%<br>Significant at the 1% level | 12% | 37% |
| ZONE 4 | 46%<br>Significant at the 1% level | 16% | 33% |
| ZONE 5 | 62%<br>Significant at the 1% level | 12% | 22% |
| ZONE 6 | 20%<br>Significant at the 1% level | 22% | 48% |

### 3.3.4. AIR TEMPERATURE EXTREMES AND TRENDS

Finally, Figure 3.14 depicts in the top row, the mean number of warm days and warm nights in a year, while the bottom row shows the mean number of cool days and cool nights. Averaging is done for the period 1980 to 2011. The average number of warm days (nights) across the region varies between 10 and 55 (22 and 53) days for the stations analysed. Cultuurtuin in Suriname showed the highest average number of warm days in a year while Grenada's Point Salines showed the least. Belmopan, Belize showed the highest number of warm nights while Lelydorp, Suriname has the least. With respect to the number of cool days (nights) the range is between 10 and 37 (18 and 36) days per year.



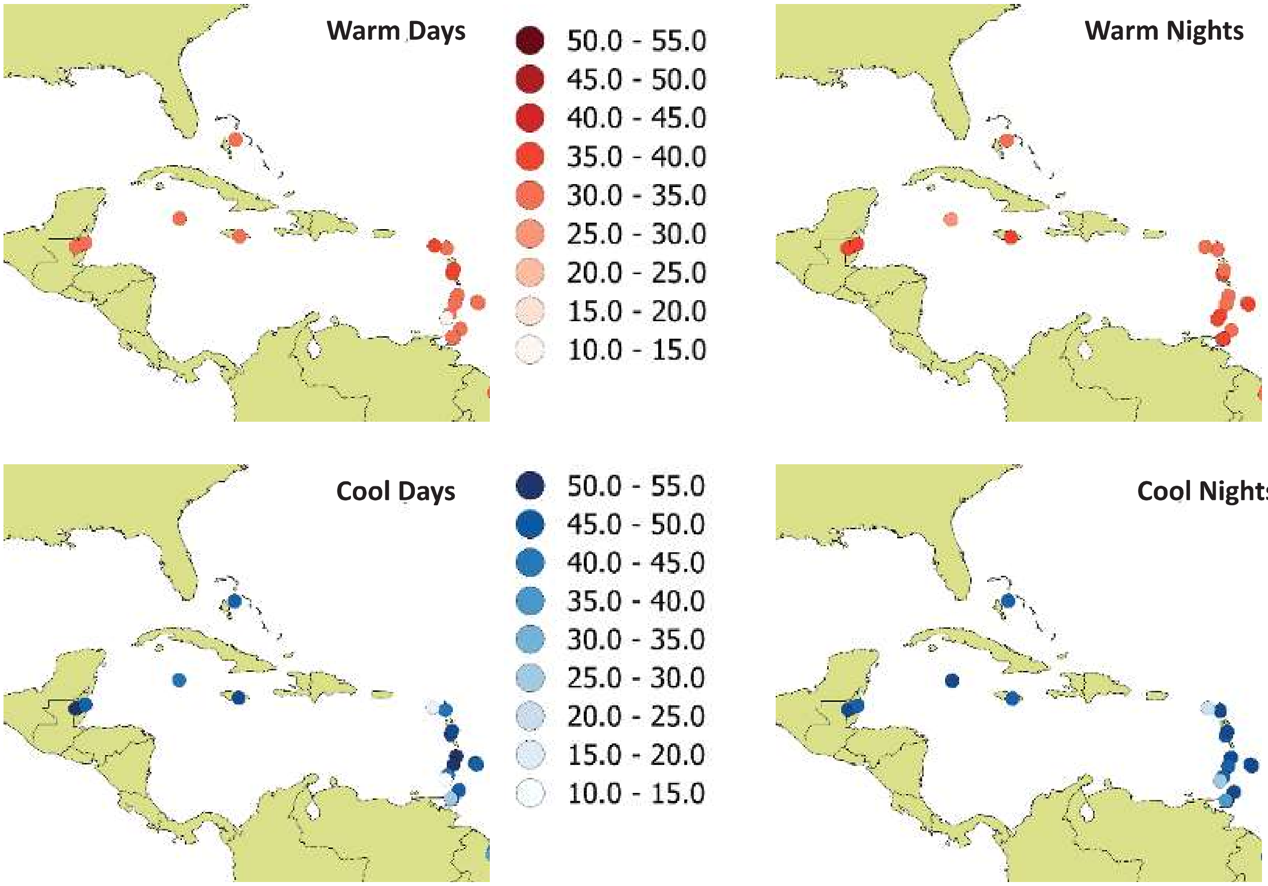



**Figure 3.14:** Top row: Warm Days and Warm Nights. Bottom row: Cool Days and Cool Nights for the Caribbean region over the period 1980 to 2011. Units are days. Data Source: CAROGEN.

Table 3.7 shows the linear trend for the extreme temperature indices. As for rainfall, data for stations in a zone are averaged. There is an increasing trend in very warm days and nights for the Caribbean as a whole (an increase of approximately 34 more days over the period) and across all zones. There is also a decreasing trend in cool days and nights for the Caribbean and across all zones except for Zone 1 which showed a negligible increase for cool days. These results are consistent with Stephenson et al. (2014). The greatest increase for warm days and warm nights was observed for Zone 5 and Zone 1 respectively. For cool days and cool nights, the greatest decrease over the period 1980 to 2011 was for Zone 5.

**Table 3.7:** Slope Estimates for Extreme Temperature Indices (1980 to 2011)

| | WARM DAYS | WARM NIGHTS | COOL DAYS | COOL NIGHTS |
|---|---|---|---|---|
| CARIBBEAN | 1.133 | 0.839 | -0.357 | -0.519 |
| ZONE 1 | 0.520 | 1.357 | 0.006 | -0.049 |
| ZONE 2 | - | - | - | - |
| ZONE 3 | 1.324 | 0.599 | -0.436 | -0.072 |
| ZONE 4 | - | - | - | - |
| ZONE 5 | 1.508 | 1.041 | -0.727 | -0.979 |
| ZONE 6 | 0.896 | 0.624 | -0.231 | -0.941 |


DO NOT
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# 4. SEA LEVEL RISE, DROUGHTS & FLOODS, HURRICANES

## 4.1. INTRODUCTION

In this chapter, historical trends in sea level, as well as trends in the occurrence of floods, droughts and hurricanes are examined. In general, the climatology of each variable is examined first, followed by a summary of what is known about historical trends. For floods, use is made of the EM-DAT database (The Emergency Events Database) (Guha-Sapir et al. 2015). As opposed to examinations of trends and variability in Caribbean temperature and rainfall records, there is far less research done on sea level rise, droughts, floods and hurricanes for the Caribbean region as a whole.

## 4.2. SEA LEVEL RISE

### 4.2.1. HISTORICAL TRENDS

Globally, sea levels rose at a rate of 1.7 ± 0.2 mm/year through the 20th century according to tide gauge records (IPCC 2013). This rate of increase for the 20th century was the fastest increase in sea level for the previous 28 centuries (Robert E. Kopp et al. 2016). Table 4.1, however, shows that this sea level rise is modest in comparison to the 3.2 ± 0.4mm/year which was recorded by satellite altimeters during the end of the 20th century and the early 21st century. This suggests an acceleration in global sea level rise, which is projected to continue with increased global warming (Church & White 2006). More recently, Yi et al. (2015) have observed that this rate has increased to 4.5 ± 0.4 mm/year for regions during the period 2010-2014.

**Table 4.1:** Mean rate of global averaged sea level rise

| PERIOD | RATE (MM/YEAR) | | INFORMATION SOURCE |
|---|---|---|---|
| 1901 AND 2010 | 1.7 ± 0.2 | Tide gauge | IPCC (2013) |
| 1993 AND 2010 | 3.2 ± 0.4 | Satellite Altimeter | IPCC (2013) |

Studies on historical Caribbean sea level trends are limited in comparison to similar studies showing trends in atmospheric variables. This is due in part to the absence of very long records. The existing studies however suggest that, in the mean, Caribbean sea level trends are very similar to the global trends.

Table 4.2 shows mean Caribbean sea level trends estimated from tide gauge records and satellite altimetry. Palanisamy et al. (2012) calculates the mean Caribbean sea level rise rate to be 1.8 ± 0.1 mm/year for the period 1950 – 2009. Torres and Tsimplis (2013) determine the rate to be 1.7 ± 1.3 mm/year over the period 1993-2010. These rates are similar to the global rate of 1.7 ± 0.2 mm/year which was shown in Table 4.1. When the mean Caribbean sea level trend measured by satellite altimetry is corrected for Global Isostatic Adjustment, it is estimated to be approximately 2.5 ± 0.4 mm/year (Torres and Tsimplis 2013).

**Table 4.2:** Mean rate of sea level rise averaged over the Caribbean basin.

| PERIOD | RATE (MM/YEAR) | INFORMATION SOURCE |
|---|---|---|
| **1950 - 2009** | 1.8 ± 0.1 | Palanisamy et al. (2012) |
| **1993 - 2010** | 1.7 ± 1.3 | Torres and Tsimplis (2013) |
| **1993 - 2010** | 2.5± 1.3 | Torres and Tsimplis (2013), after correction for Global Isostatic Adjustment (GIA) |

The examined historical records also indicate that there is regional variation in the rate of sea level rise i.e. it is not uniform across the Caribbean. Figure 4.1 and Table 4.3 illustrate this. Figure 4.3 shows sea level trends for different tide gauge stations around the Caribbean region. The inconsistencies in record lengths across the region are noted. Table 4.3 gives the calculated trend for each station. Both the figure and the table are adapted from Torres and Tsimplis (2013).

Notwithstanding the station examined, there is a general increasing trend in the sea level of the Caribbean region i.e. there are no negative trends. The sea level rise varies from 0.26 mm/year off the coast of Venezuela, to as high as 10.76 mm/year for the Port-au-Prince, Haiti station. Figure 4.2 shows a map of how these rates differ across the region. The map is constructed using the Mean Reconstruction sea level (MRESL) dataset. Tide gauge records are a major data component used to develop the MRESL. However other components such as post glacial rebound and tectonics are also taken into account. The variation in sea level rise rates across the region is evident in the plot with largest increasing trends found in the southern Caribbean close to the South American continent.

The mean sea level of the Caribbean region also varies on decadal and interannual time scales. The interannual variations are evident in the time series plots of Figure 4.1. Caribbean sea level is highly correlated with El Niño-Southern Oscillation (ENSO) especially since the mid-1980s, with larger increases in sea levels occurring during stronger El Niño events (Palanisamy et. al. 2012; Torres et al. 2013; Torres and Tsimplis 2014; Blunden et al. 2016). This may have led to sea levels reaching as high as 11.3 cm above mean sea level during the 2015 El Niño event. Recent studies also show a significant correlation between the interannual variability in sea level and hurricane activity (Torres and Tsimplis 2014). This is especially true for the post 2000 period, during which hurricane intensity and sea level interannual variability have both increased.

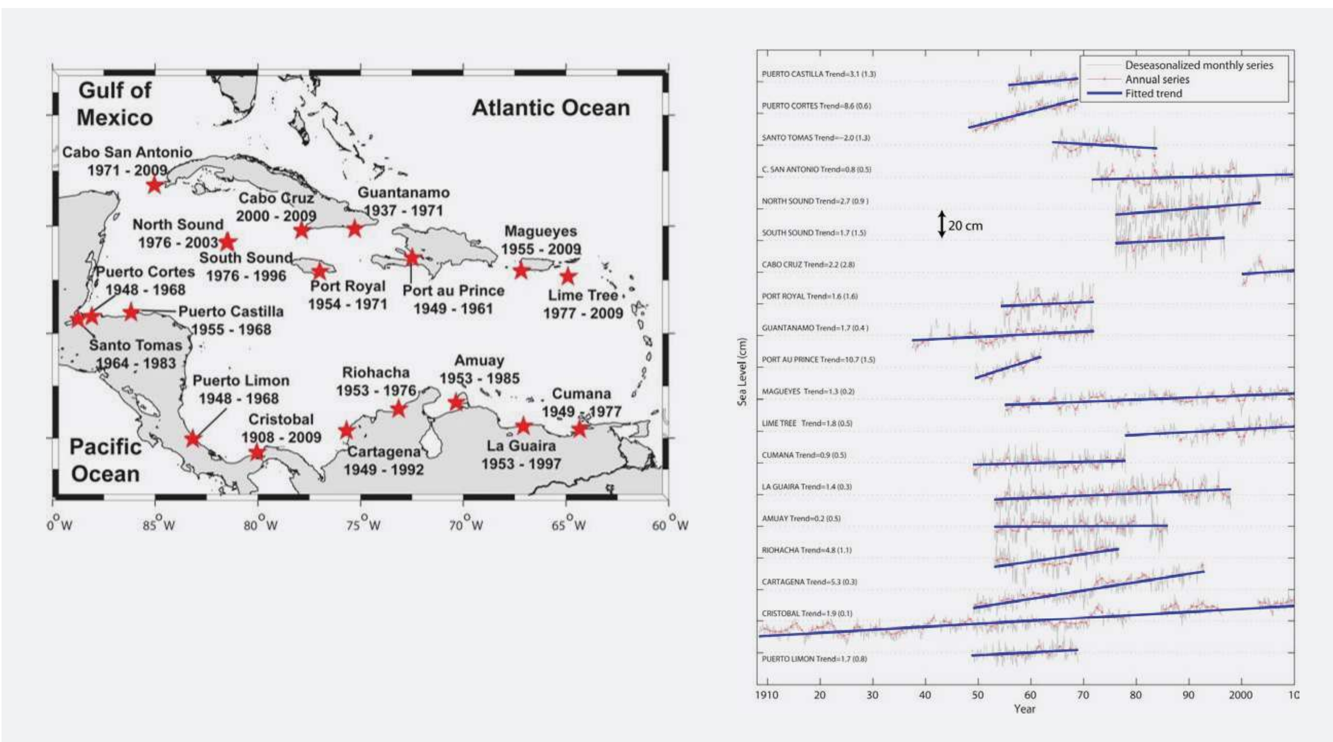


**Figure 4.1:** a) Location of tide gauge stations and time series start and end year. b) Tide gauge observed sea-level trends computed from all available data. Monthly time series after the removal of the seasonal cycle (gray), the linear trend (blue), and the annual series (red) are also shown. The trends (and 95% error) in mm/yr. From Torres and Tsimplis (2013).

**Table 4.3:** Tide gauge observed sea-level trends for Caribbean stations shown in Figure 4.1. Table adapted from Torres & Tsimplis (2013)

| | Country | Lat (N) | Lon (W) | Span years | % of data | Trend (mm/ year) | Months | Gauge corrected |
|---|---|---|---|---|---|---|---|---|
| **P. LIMON** | Costa Rica | 10 | 83 | 20.3 | 95.1 | 1.76±0.8 | 216 | 2.16±0.9 |
| **CRISTOBAL** | Panama | 9.35 | 79.9 | 101.7 | 86.9 | 1.96±0.1 | 566 | 2.86±0.2 |
| **CARTAGENA** | Colombia | 10.4 | 75.6 | 44 | 90 | 5.36±0.3 | 463 | 5.46±0.3 |
| **RIOHACHA** | Colombia | 11.6 | 72.9 | 23.8 | 95.8 | 4.86±1.1 | 273 | 4.86±1.1 |
| **AMUAY** | Venezuela | 11.8 | 70.2 | 33 | 93.4 | 0.26±0.5 | 370 | 0.26±0.5 |
| **LA GUAIRA** | Venezuela | 10.6 | 66.9 | 45 | 98.9 | 1.46±0.3 | 534 | 1.56±0.3 |
| **CUMANA** | Venezuela | 10.5 | 64.2 | 29 | 98.6 | 0.96±0.5 | 331 | 0.76±0.6 |
| **LIME TREE** | US Virgin Islands | 17.7 | 64.8 | 32.2 | 81.9 | 1.86±0.5 | 316 | 1.56±0.5 |
| **MAGUEYES** | Puerto Rico | 18 | 67.1 | 55 | 96.2 | 1.36±0.2 | 635 | 1.06±0.2 |
| **P. PRINCE** | Haiti | 18.6 | 72.3 | 12.7 | 100 | 10.76±1.5 | 144 | 12.26±1.5 |
| **GUANTANAMO** | Cuba | 19.9 | 75.2 | 34.6 | 89.9 | 1.76±0.4 | 258 | 2.56±0.6 |
| **PORT ROYAL** | Jamaica | 17.9 | 76.8 | 17.8 | 99.5 | 1.66±1.6 | 212 | 1.36±1.6 |
| **CABO CRUZ** | Cuba | 19.8 | 77.7 | 10 | 90 | 2.26±2.8 | 108 | 2.16±2.8 |
| **SOUTH SOUND** | Cayman | 19.3 | 81.4 | 20.8 | 87.6 | 1.76±1.5 | 219 | 1.26±1.5 |
| **NORTH SOUND** | Cayman | 19.3 | 81.3 | 27.7 | 89.2 | 2.76±0.9 | 296 | 2.26±0.9 |
| **C. SAN ANTONIO** | Cuba | 21.9 | 84.9 | 38.3 | 76.7 | 0.86±0.5 | 353 | 0.36±0.5 |
| **SANTO TOMAS** | Mexico | 15.7 | 88.6 | 20 | 85.4 | 2.06±1.3 | 205 | 1.76±1.3 |
| **P. CORTES** | Honduras | 15.8 | 87.9 | 20.9 | 98 | 8.66±0.6 | 224 | 8.86±0.7 |
| **P. CASTILLA** | Honduras | 16 | 86 | 13.3 | 100 | 3.16±1.3 | 160 | 3.26±1.3 |

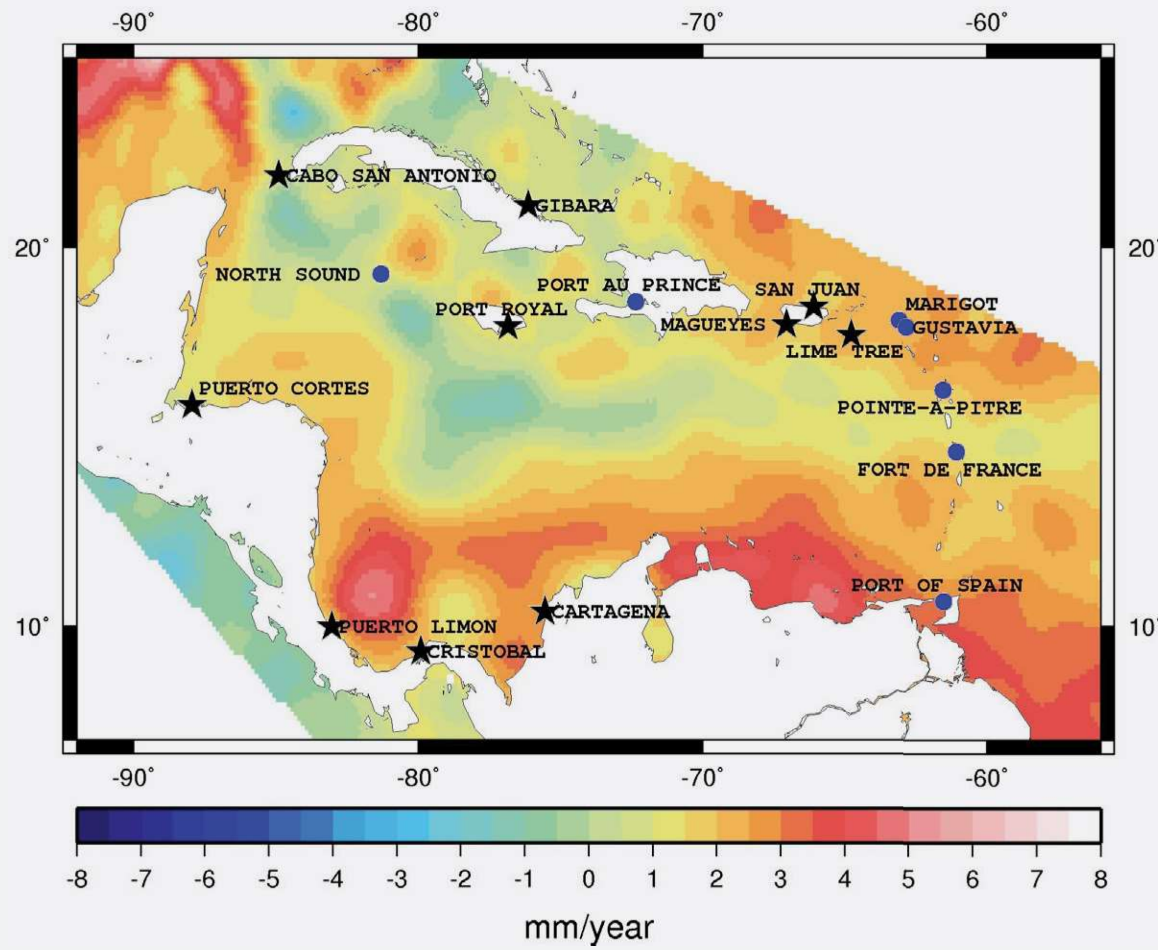


**Figure 4.2:** Mean Reconstruction Sea Level (MRESL) from 1950- 2009. Figure Source: Palanisamy et al. (2012).

## 4.3. HURRICANES

### 4.3.1. CLIMATOLOGY

The hurricane season in the North Atlantic spans June to November. This coincides with the period when the Gulf of Mexico, the Caribbean Sea, and the north tropical Atlantic are most conducive to convective activity. During this time of the year, the region is characterised by weak easterly trade winds, decreased vertical wind shear, and SSTs in excess of 26oC (see again Box 3.1). In tandem, these create ideal conditions for tropical cyclone (TC) activity.

The climatology of hurricanes and tropical storms in the tropical Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico is shown in Figure 4.3. It is to be noted that although storms and hurricanes generally occur between June 1 and November 30 (i.e. the official hurricane season), it does not preclude storm or hurricane activity in May or December. The peak of the North Atlantic season is from mid-August to late October, with a primary peak around September 10th. A secondary peak occurs around the middle of October, which is mainly for the Caribbean Sea and the Gulf of Mexico region, after which the number of storms drops off quickly through the end of the season.

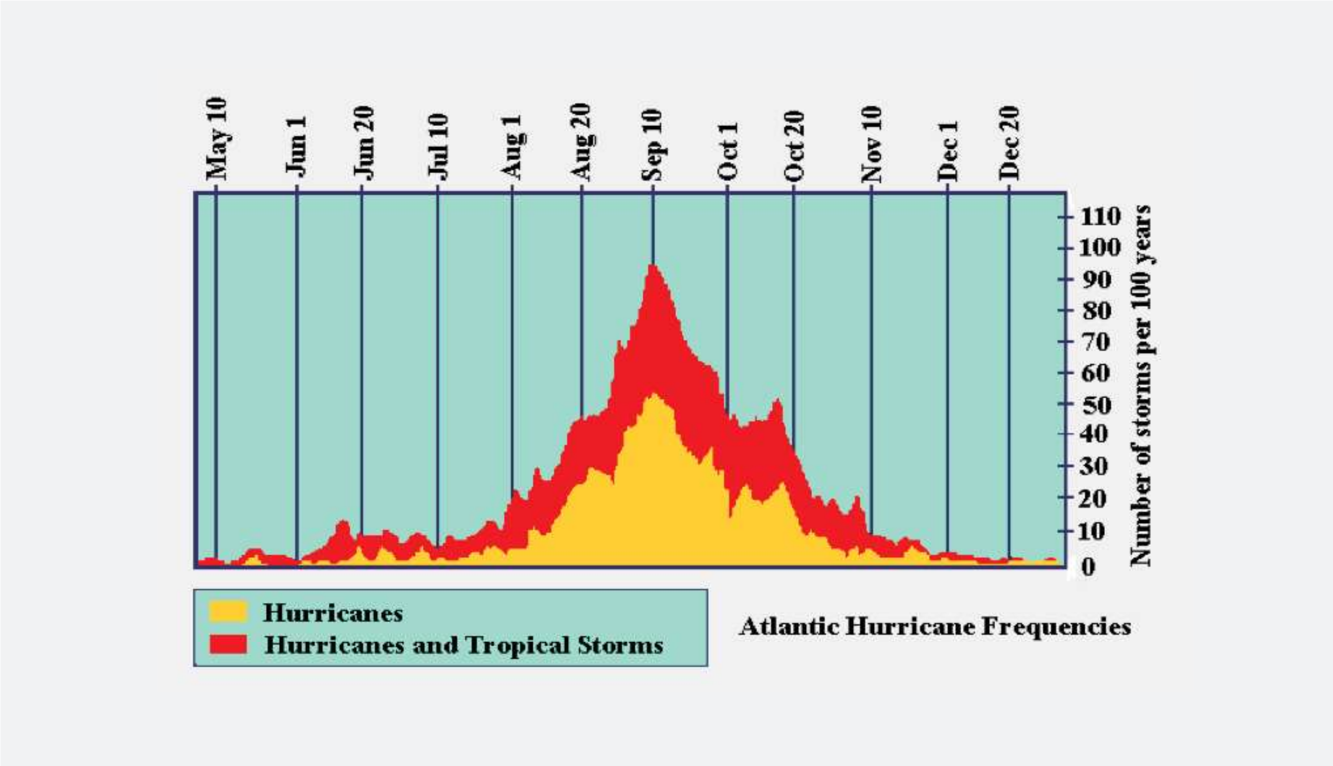


**Figure 4.3:** Storm frequency during the Atlantic Ocean hurricane season. Source: NOAA.

Figure 4.4 shows the mean areas of origin and prevailing tracks during selected months of the hurricane season. From June through August, the areas of origin shift from the western Caribbean Sea and Gulf of Mexico (June) into the Atlantic Ocean (August-September). This coincides with the eastward expansion of the Atlantic warm pool which results in water temperatures becoming warmer in the north tropical Atlantic (see Section 3.2.1) thereby allowing easterly waves coming off the African coast to develop into storms and hurricanes. By October, the water temperatures in the north tropical Atlantic east of the Caribbean basin start to cool and wind shear increases, and storm genesis and activity generally shifts back into the Caribbean Sea and Gulf of Mexico, where the water temperatures are still very warm.

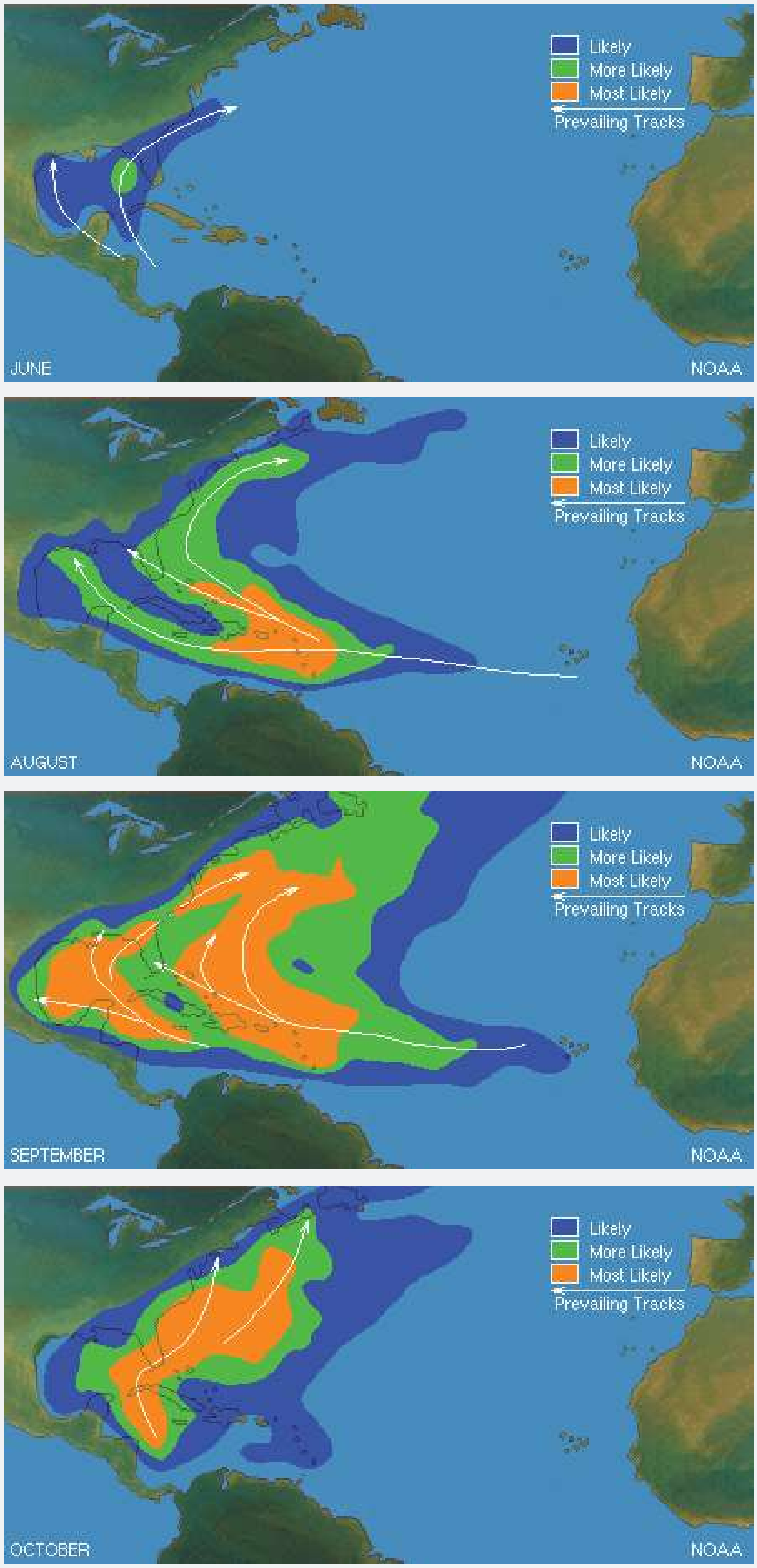


**Figure 4.4:** Zones of likely origin and track density of storms by month during the hurricane season from August-October. Source: NOAA.

### 4.3.2. TRENDS

Tropical cyclone activity can be measured with a variety of metrics for intensity, frequency, and duration. Though storm records for the North Atlantic region date as far back as the mid-1800s (see for example Figure 4.5), analysis of trends is generally restricted to the period after 1950 to coincide with the instrumental period beginning in the mid-1950s. This period signifies the start of the use of aircraft reconnaissance. Since the late 1970s satellite imagery has also been used to verify the state of tropical storms.

Most measures of Atlantic hurricane activity show a marked increase since the early 1980s when high-quality satellite data became available (Bell et al. 2012; Bender et al. 2010; Emanuel 2007; Landsea and Franklin 2013). These include measures of intensity, frequency, and duration as well as the number of strongest (category 4 and 5) storms. Figure 4.5 shows the total number of storms passing through the North Atlantic region over the period 1950-2019. The North Atlantic has seen a significant increase in tropical cyclone activity since 1995 with a distinct increase in the number of intense (category 4 and 5) storms (Webster et al. 2005). Though there is a significant increase in recent research suggesting a global warming link with recent changes in hurricane activity, in particular with increases in the number of intense hurricanes, there is still a lack of consensus on the extent of its contribution, since other long term modulators of SST in the north tropical Atlantic such as the Atlantic Multi-decadal Oscillation (AMO) are in a positive (enhancement) phase.

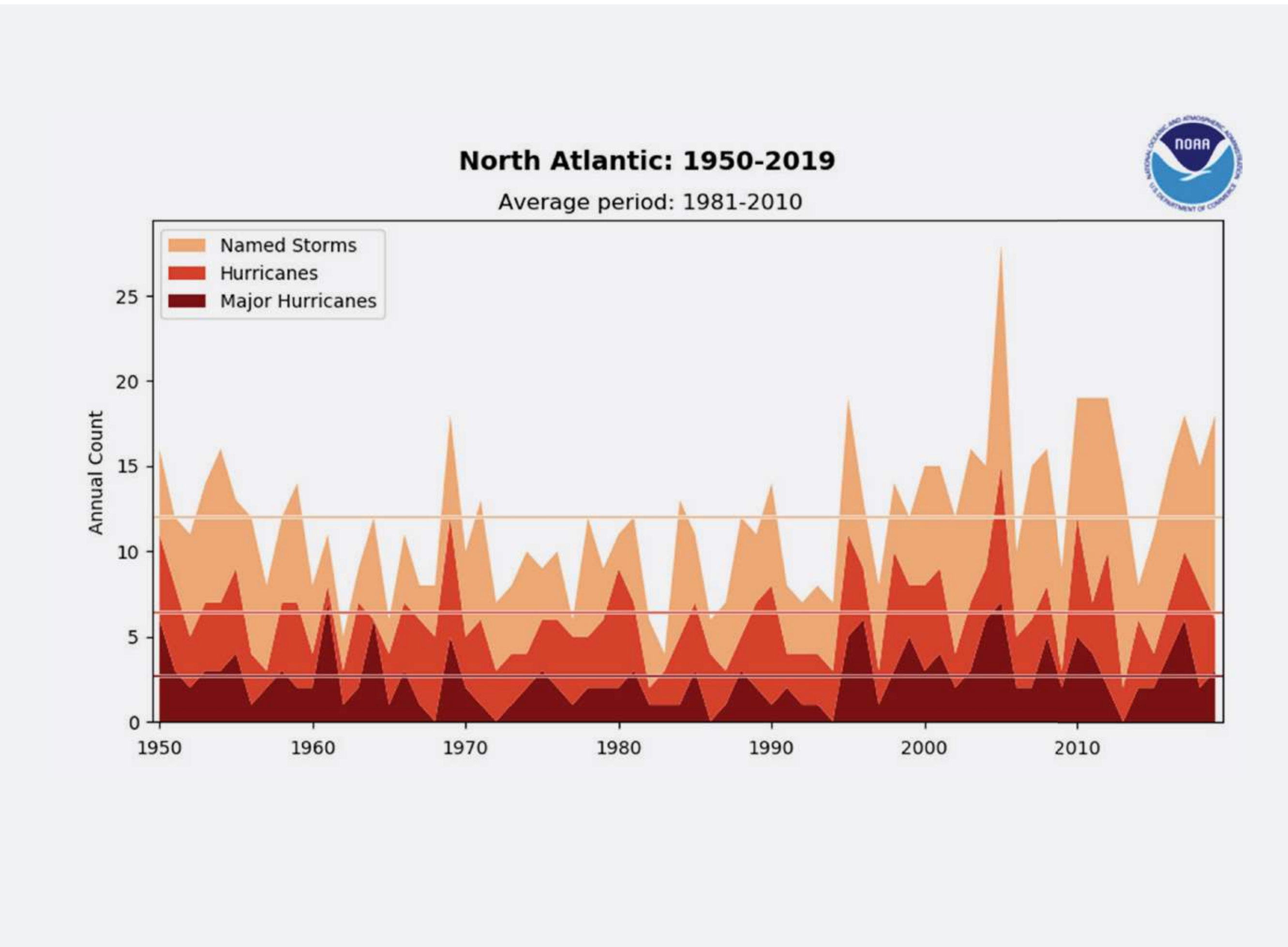


**Figure 4.5:** The number of named storms, hurricanes and major hurricanes per year passing through the North Atlantic and Gulf of Mexico from 1950-2019. Source: NOAA 2020.

The El Niño-Southern Oscillation phenomenon plays a significant role in modifying hurricane activity in the North Atlantic from year to year i.e. notwithstanding long term trends. El Niño contributes to fewer Atlantic hurricanes while La Niña contributes to more Atlantic hurricanes. El Niño produces upper level westerly wind anomalies and lower level easterly wind anomalies across the tropical Atlantic, which together result in higher vertical wind shear. El Niño and La Niña also influence where the Atlantic hurricanes form. During El Niño events, fewer hurricanes and major hurricanes develop in the deep Tropics from African easterly waves. During La Niña, more hurricanes form in the deep Tropics from African easterly waves, with these systems having a much greater likelihood of becoming major hurricanes and eventually threatening the U.S. and Caribbean.

Figure 4.6 shows all the named storms between 1980 and 2016 that have passed through each of the six rainfall zones previously defined in Chapter 3 and depicted in Figure 3.1. Table 4.4 gives the breakdown by category. All the zones have similar total activity except for Zones 1 and 6. Zone 2 had an even distribution of storms across all categories. Zone 4 had the largest number of category 1 storms while Zone 3 had the highest number of category 4 storms. Zones 4 and 5 have the highest frequency of storms being category 1 storms, with category 4 storms being second. Zone 3, however, has its highest frequency of storms being category 4 storms, with category 1 storms being second. Zone 3 has the most frequent storm tracks of category 4 among all the zones investigated. Zone 6 (Grenada, Guyana and Suriname) shows zero storm activity for the period.

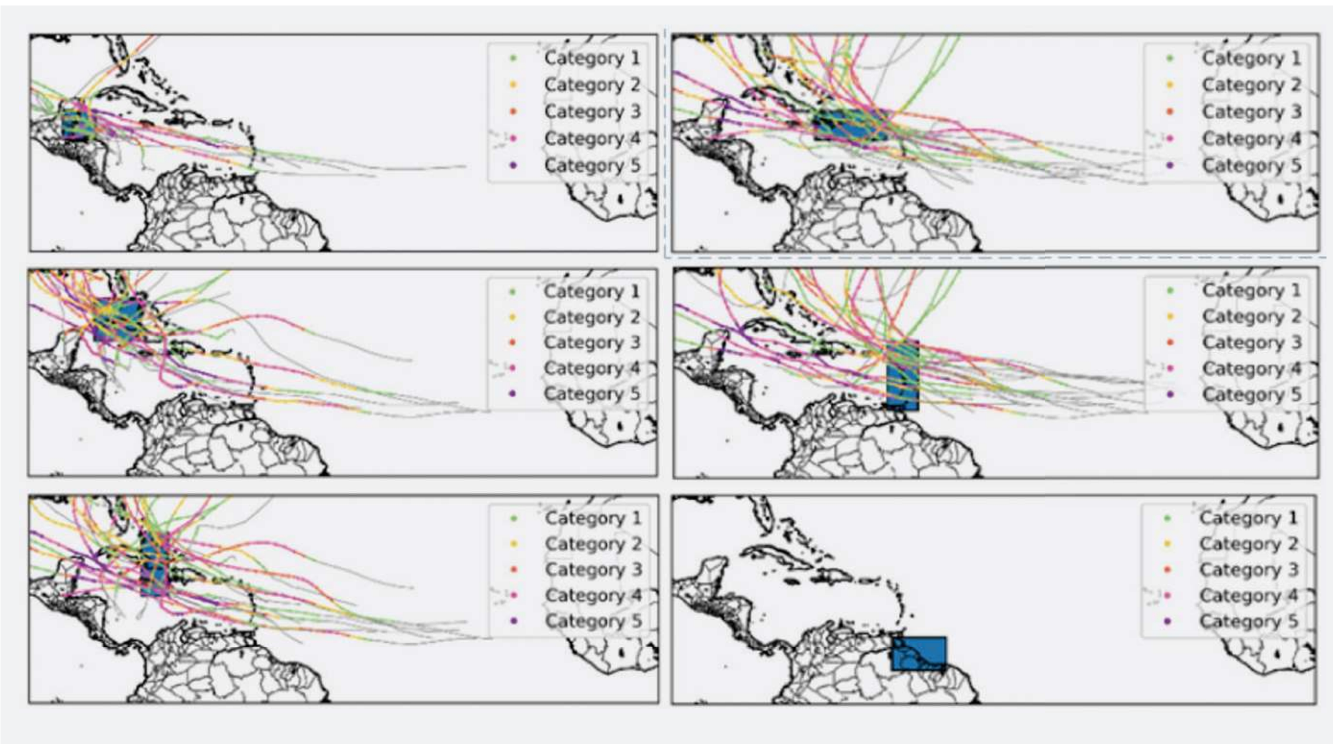


**Figure 4.6:** Storms and Hurricane tracks for zones 1-6 from 1980-2016. Left panels: Zones1, 2 and 3. Right panels: Zones 4,5 and 6.

**Table 4.4:** Named storms by decades that have passed within 200 km of the identified country representing each zone. The table also shows the category of the storm from 1980-2016.

| ZONES | COUNTRIES IN ZONE | NUMBER OF HURRICANES IMPACTING THE ZONES BY CATEGORY | | | | | |
|---|---|---|---|---|---|---|---|
| | | CATEGORY 1 | CATEGORY 2 | CATEGORY 3 | CATEGORY 4 | CATEGORY 5 | TOTAL |
| 1 | Belize | 2 | 3 | 2 | 4 | 3 | 14 |
| 2 | - | 6 | 5 | 4 | 5 | 3 | 23 |
| 3 | Jamaica and Bahamas | 9 | 2 | 3 | 11 | 0 | 25 |
| 4 | Haiti | 12 | 1 | 4 | 7 | 1 | 25 |
| 5 | Anguilla, Antigua & Barbuda, Barbados, British Virgin Island, Dominica, Montserrat, St Kitts & Nevis, St Lucia and St Vincent, the Grenadines & Trinidad and Tobago | 10 | 4 | 3 | 7 | 0 | 24 |
| 6 | Grenada, Guyana, Suriname | 0 | 0 | 0 | 0 | 0 | 0 |
| **TOTAL** | | **39** | **15** | **16** | **34** | **7** | **111** |

## 4.4. DROUGHTS & FLOODS

### 4.4.1. FLOODS

The Caribbean region is prone to flooding given its susceptibility to storms and hurricanes. Burgess et al. (2018) using the EM-DAT disaster database (Guha-Sapir et al. 2015) show that there were at least 370 occurrences of meteorological related disasters between 1960 and 2013 in 22 Caribbean countries (Figure 4.7). Tropical cyclones (264 or 71.4%) and riverine flooding (59 or 15.9%) accounted for the majority of the occurrences. Tropical cyclones also accounted for 94.5% of the damages in the Caribbean countries from meteorological disasters since 1960 according to the EM-DAT database. In a similar study, Acevedo (2014) showed that at least 250 storm and flooding events impacted 12 Caribbean countries between 1970 and 2009, resulting in approximately USD20 billion in damages (2010 dollars).

Figure 4.8 shows a breakdown by country of flooding events listed in the EM-DAT database between 1900 and 2016. There is an uneven distribution across the Caribbean with the islands of the Greater Antilles experiencing the highest number of events. In particular, Haiti is shown to experience the highest number of flooding events among the countries examined.

Burgess et al. (2018) also examined how occurrences of Caribbean meteorological disasters have changed from 1960 to 2013. They find that occurrences have increased from an annual average of 1.7 events for the period prior to 1980 to 10.8 events after 1980 (Figure 4.9). They suggest there may be a link to warming in global surface air temperatures.

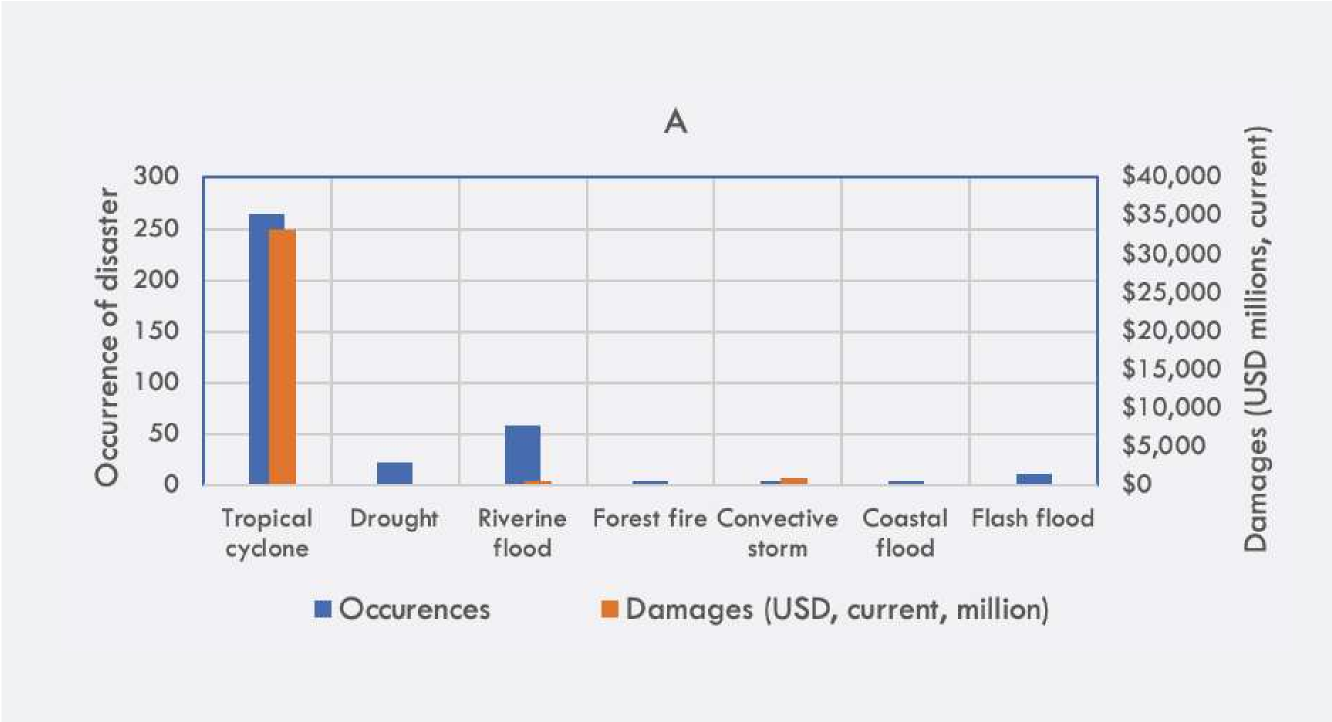


**Figure 4.7:** Occurrence and damages in the Caribbean (USD millions, current) categorized by disaster type for the period 1960 to 2013. Data Source: EM-DAT Database. Adapted from Burgess et al (2018).

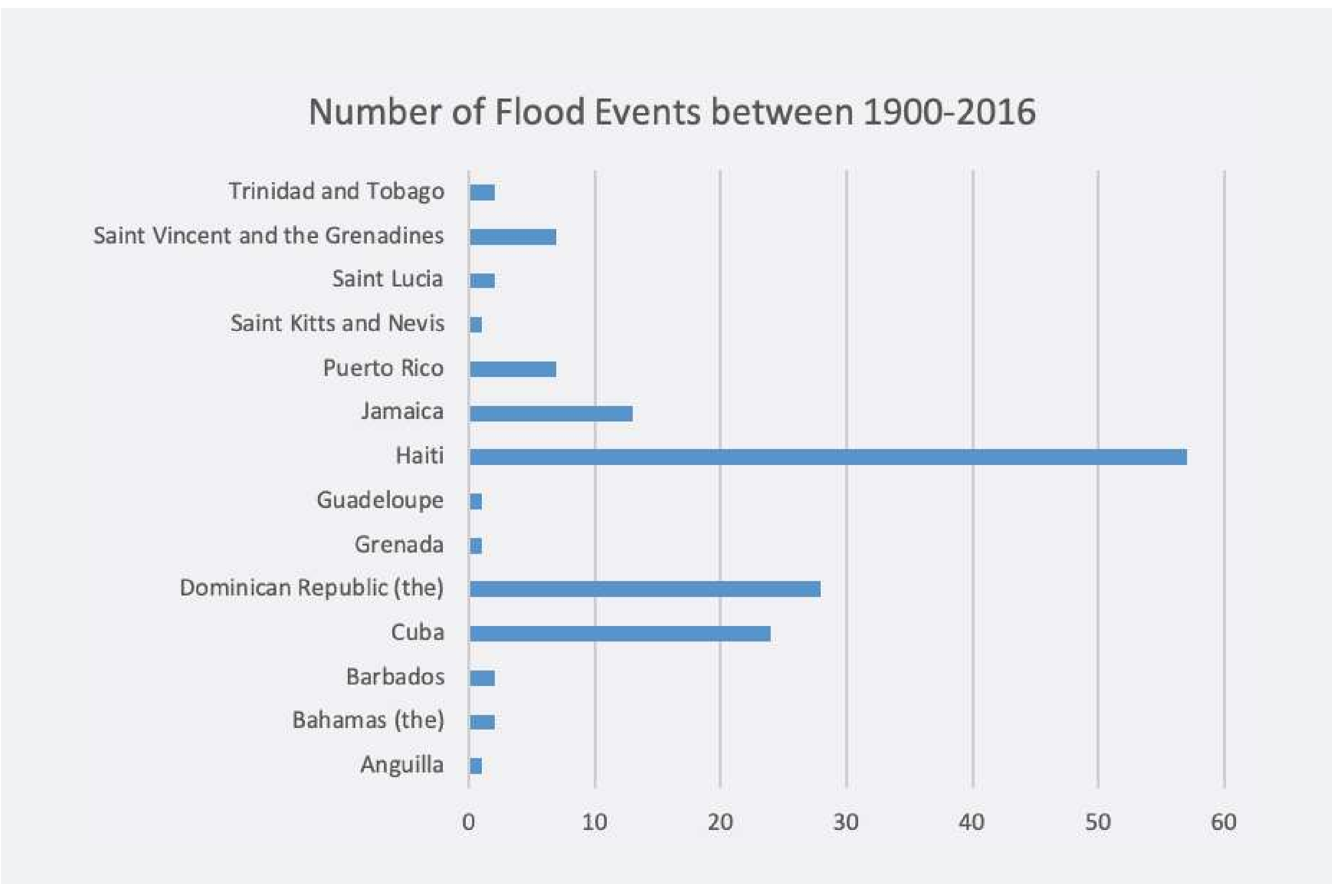


**Figure 4.8:** Number of flood events across selected Caribbean countries during 1900-2016. Data source: EM-DAT Database.

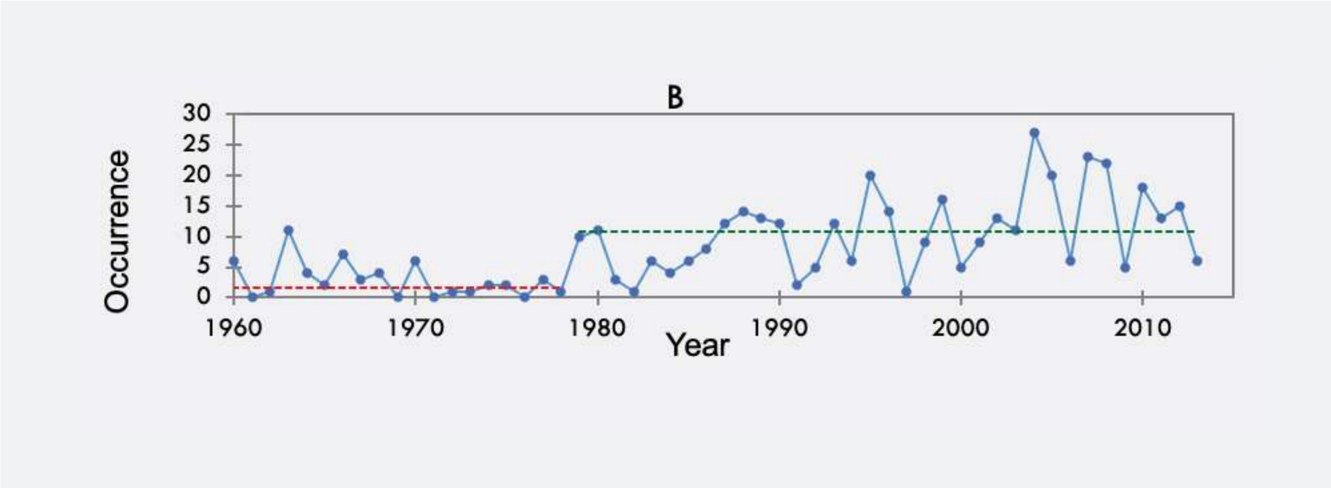


**Figure 4.9:** Occurrence of Caribbean meteorological disasters from 1960 to 2013. Source Data: EM-DAT database. Adapted from Burgess et al. (2018).

### 4.4.2. DROUGHT

The Caribbean region faces significant challenges due to drought. However, because of its slow-onset nature, it is often overlooked. During the past decades, the Caribbean has experienced several drought events, with many seemingly linked to years with El Nino events. These include events in 1957, 1968, 1976-77, 1986-1987, 1991, 1994, 1997-1998, 2009-2010, and again in 2013-2016. Numerous drought indices have been used to characterize the stage of drought or the severity of a drought episode. The following discussion draws on the conclusions of studies which use respectively the Standardized Precipitation Index (SPI) and the self-calibrating Palmer Drought Severity Index (scPDSI). In the first study (Walters 2018), SPIs are used to examine the spatial distribution of drought occurrence across the Caribbean between 1951 and 2000. In the second set of studies (Herrera and Ault 2017; and Herrera et al. 2018), scPDSI is used to focus on severe drought events between 1950 and 2016.

Walters (2018) uses the Standardized Precipitation Index (SPI) to characterize the rarity of extreme and moderate drought events in different parts of the Caribbean on a variety of time scales. SPIs were derived from time series of rainfall representing four zones in the Caribbean, which overlap with the six rainfall zones examined in Chapter 3. The four zones capture drought variation in the far north Caribbean (western Cuba and the Bahamas), a Jamaica region (eastern Cuba, Jamaica, Turks and Caicos and the western half of Hispaniola), the eastern Caribbean (Puerto Rico and the Lesser Antilles) and the southern Caribbean (Trinidad and Tobago and Guyana).

Major conclusions from the Walters (2018) study are:

- » The far north Caribbean seems the least prone to extreme drought.
- » There are likely different features modulating the occurrence of drought, depending on the region of the Caribbean being considered, as the SPIs across the four zones do not always behave in phase. Of the four regions, the eastern and southern Caribbean exhibit the highest degree of correlation.
- » The Jamaica region experienced extreme droughts in the mid-1960s, mid-1970s, and again in the early 1990s. The far north Caribbean experienced extreme drought conditions in the 1950s, 1963 and 1972, and moderate drought after 1975. The eastern and south Caribbean experienced extreme drought conditions in the 1960s and 1970s, with the eastern Caribbean experiencing these conditions again in the mid-1990s.
- » After 1983, the south Caribbean and the Jamaica region tend to have predominantly negative SPIs suggesting a shift toward drier conditions. This is also true for the eastern Caribbean after 1990.
- » Though region wide droughts (i.e. when all SPIs for all zones are simultaneously negative) are not common over the period analysed (up to 2000), the mid to late 1970s stand out.

» Timescales of 2-3 years and 9-13 years characterise drought occurrence across most of the Caribbean zones. A 3-6 year timescale also occurs in the eastern Caribbean, and a 5-6 year signal occurs in the south Caribbean.

» All zones generally seem to exhibit correlations with tropical and equatorial Pacific SSTs, suggesting a potential link to El Nino events. However, whereas the El Nino event seems to bring dry conditions across most of the Caribbean, it seems to enhance wet conditions in the far north Caribbean. The Caribbean Sea is correlated with the Jamaica region, the far north Caribbean, and the eastern Caribbean, but not the south Caribbean.

In two other recent studies, Herrea and Ault (2017) and Herrera et al. (2018) use scPDSI to show that since 1950, the Caribbean has experienced a general drying trend (Figure 4.10). They however point out that the trend is not homogeneous across the region, with, in particular, the far north Caribbean seeing a tendency to be wetter. Like Walters (2018), they also confirm the tropical Pacific and tropical north Atlantic as significant modulators of drought variability in the region.

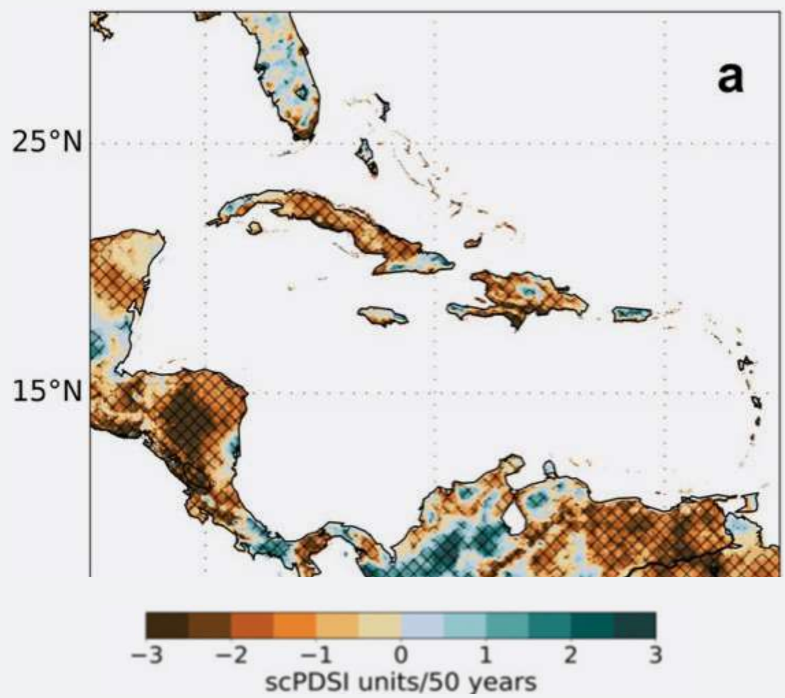


**Figure 4.10**: Linear trends showing the change of the scPDSI during the 1950–2016 interval Brown colours represent drying trend and cyan colours a wetting trend. In (a) and (b), the hatching means a significant trend ($p < 0.05$) at the 95% level. From Herrera and Ault (2017).

The studies also show that the region as a whole has experienced severe droughts in 1974–77, 1997/98, 2009/10, and 2013–16 (Figure 4.11). Of the four periods, the 2013-2016 drought was the most severe experienced by the Caribbean, as virtually the entire region experienced a Pan-Caribbean drought. During the three-year period, drought conditions in 2014 ranked as the most severe since 1950 due to the greater area covered. However, 2015 ranked as the driest year during the 2013–16 droughts and had the highest potential evapotranspiration (PET) and temperatures which may have added to the severity of the drought. Though the 2013-2016 Caribbean drought can be associated with the 2015/16 El Nino event, Herrera et al (2018) also suggest that global warming likely contributed to ~15–17% of drought severity for the 2013-2016 event, by increasing evapotranspiration rates and accounting for ~7% of land area under drought. That is, their results indicate that anthropogenic warming is likely already increasing drought risk in the Caribbean.

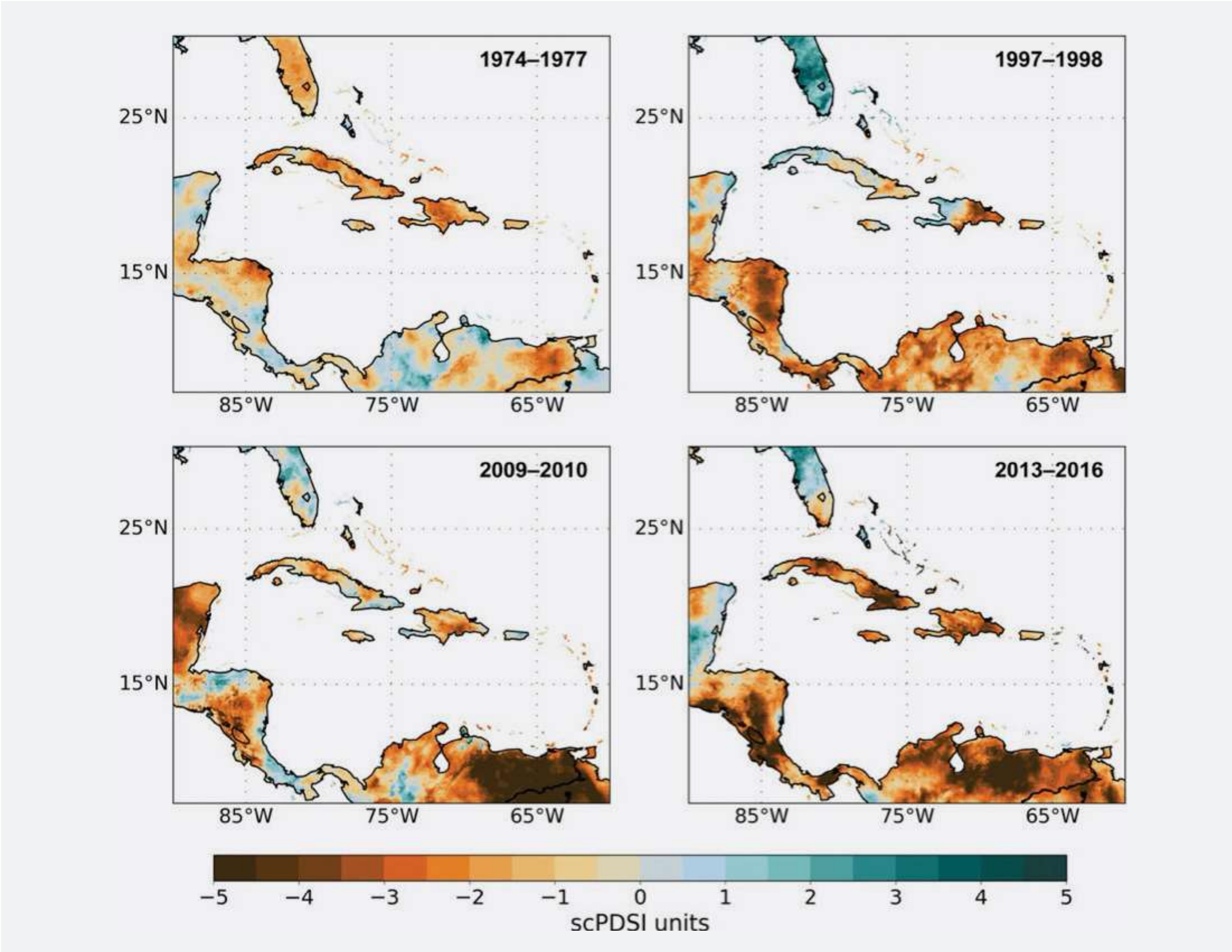


Figure 4.11: Major droughts in the Caribbean between 1950 and 2016 of at least one year in duration. From Herrera and Ault (2017).