Recent changes in climate extremes in the Caribbean region

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[1] A January 2001 workshop held in Kingston, Jamaica, brought together scientists and data from around the Caribbean region and made analysis of indices of extremes derived from daily weather observation in the region possible. The results of the analyses indicate that the percent of days having very warm maximum or minimum temperatures increased strongly since the late 1950s while the percent of days with very cold temperatures decreased. One measure of extreme precipitation shows an increase over this time period while the one analyzed measure of dry conditions, the maximum number of consecutive dry days, is decreasing. These changes generally agree with what is observed in many other parts of the world. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; *KEYWORDS:* Caribbean, climate, extremes, temperature, precipitation, climate change

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1. Introduction

[2] In the 1980s, considerable work was done analyzing long-term monthly mean temperature data and we learned that the globe has been warming during the last century [e.g., *Jones et al.*, 1982; *Hansen and Lebedeff*, 1987]. In the early 1990s, the focus of this type of climate change research shifted to mean monthly maximum and minimum temperature data [e.g., *Karl et al.*, 1993]. Since century-scale digital mean monthly maximum and minimum temperature data are not as widely available as mean monthly temperatures, the analysis was limited to the period since 1950 and indicated that, during the last few decades, mean monthly minimum temperatures have generally been warming faster than mean monthly maximum temperatures. However, monthly averages cannot reveal changes in extremes, which are likely to be very important to individuals. To provide some insights in changes to extremes for the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report [*Houghton et al.*, 2001], in 1998, C. Folland of the Hadley Centre organized an expert team meeting on indices under the auspices of the Joint World Meteorological Organization Commission for Climatology/World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR) Working Group on Climate Change Detection (WGCCD; *Peterson et al.* [2001]). The expert team focused primarily on indices that could be derived from daily data.

[3] The results of this meeting were two fold. First, a fairly comprehensive list of indices was developed (see the Royal Netherlands Meteorological Institute's (KNMI) web page with detailed information on the indices: http://www.knmi.nl/samenw/eca/htmls/index2.html). Second, an analysis of as much of the globe as possible was undertaken. This "global" analysis, presented by *Frich et al.* [2002], indicated that generally several measures of heavy precipitation increased since 1950 and some measures of temperature extremes, such as the number of minimum temperature observations above the 90th percentile, also went up. But unfortunately, as *Frich et al.* [2002] indicated, there are large areas where no digital daily data were available for analysis.

[4] The WGCCD undertook several efforts to fill in the blank areas. They undertook internationally coordinating the analysis of a defined set of indices derived from daily

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Table 1. Stations Used in This Analysis

Precipitation Data[a]	Daily Maximum or Minimum Temperature Data[a]	Number of Years With Data From 1958–1999	Latitude	Longitude	Elevation,[b] m	Station Name	Country
P	T	30	13.17	−59.59	−999	BARBADOS	BARBADOS
P	T	40	17.53	−88.30	5	PSWGIA	BELIZE
P		7	16.13	−88.85	6	PUNTA GORDA AGSTAT	BELIZE
P		7	17.01	−88.51	120	MIDDLESEX STANN CREEK	BELIZE
P		7	18.25	−88.45	10	SANTA CRUZ (BSI) COROZAL	BELIZE
P	T	30	17.31	−88.12	61	CENTRAL FARM	BELIZE
P	T	42	18.48	−69.92	14	SANTO DOMINGO	DOMINICAN REPUBLIC
P		8	19.78	−72.80	−999	BASSIN BLEU	HAITI
P		7	19.45	−71.80	−999	JEAN RABEL	HAITI
P		18	18.20	−73.75	−999	CAYES	HAITI
P		11	19.13	−71.98	−999	PAPAYE(HINCHE)	HAITI
P		23	17.39	−62.81	25	AGRONOMY	ST. KITTS
P		21	17.37	−62.82	143	OLIVEES	ST. KITTS
P		21	17.36	−62.83	142	STAPLETON	ST. KITTS
P		23	17.35	−62.80	56	WINGFIELD	ST. KITTS
P	T	32	26.55	−78.70	11	FREEPORT	BAHAMAS
P	T	41	10.37	−61.21	15	PICARO IAP	TRINIDAD AND TOBAGO
P	T	40	19.90	−75.15	16	GUANTANAMO BAY	U.S. - CUBA
P	T	32	25.83	−81.38	2	EVERGLADES	U.S. - FLORIDA
P	T	42	24.55	−81.75	1	KEY WEST WSO AIRPORT	U.S. - FLORIDA
P	T	29	18.27	−66.85	445	LARES 3 SE	U.S. - PUERTO RICO
P	T	40	18.02	−66.52	21	PONCE 4 E	U.S. - PUERTO RICO
P	T	42	18.43	−66.00	3	SAN JUAN WSFO AP	U.S. - PUERTO RICO
P	T	30	18.25	−66.68	159	UTUADO	U.S. - PUERTO RICO
P		23	18.33	−64.67	46	EAST END	U.S. - VIRGIN ISLANDS
P	T	20	18.33	−64.90	61	ESTATE FORT MYLNER	U.S. - VIRGIN ISLANDS
P		23	18.35	−64.92	197	WINTBERG	U.S. - VIRGIN ISLANDS
P		39	12.20	−68.96	62	HATO AP - CURACOA	NETHERLANDS ANTILLES
P	T	23	19.17	−81.21	3	GRAND CAYMAN	CAYMAN ISLANDS
	T	13	13.13	−61.20	13	ST VINCENT	ST. VINCENT

[a] Column 1 is a P if there is precipitation data available, and column 2 is a T if there are daily maximum or minimum temperature data available.
[b] Here, −999 means missing.

data so that other researchers could calculate the indices using exactly the same formulas. If the same formulas were used, additional analyses would fit seamlessly into the *Frich et al.* [2002] "global" picture. The WGCCD supported the development of indices software using Excel spread sheets as many researchers in the areas of the world not represented by *Frich et al.* [2002], such as Central and South America, Africa, and southern Asia, have considerable expertise using spread sheets. Lastly, the WG sponsored regional climate change workshops to undertake such analyses. These workshops were modeled after the very successful Asia Pacific Network workshops [*Manton et al.*, 2001].

[5] This is a report of the results of the Caribbean Regional Climate Change workshop held in Kingston, Jamaica in January 2001 [*Petersen et al.*, 2001]. Hosted by the University of the West Indies, the workshop attracted participants from 18 of the 21 meteorological services in the region. It was a true "workshop." The participants brought data with them. Their time was split between lectures, seminars and discussions, and hands-on data analysis at the University of the West Indies computer center. In addition to providing preliminary analysis of the data, the workshop clearly fostered considerable interest and enthusiasm for daily data and data archaeology.

2. Data

[6] The region has significant problems when it comes to digital daily data. Many island countries have not yet digitized the paper archive data they have available. One country, Jamaica, had a considerable digital and paper archive that was lost in a fire in 1992. After the workshop, the participants collected some additional data. As a result, data from 30 stations were used (see Table 1). These data are primarily from Caribbean islands, however, one coastal Florida station was used and 4 stations from Belize. Belize was the only Central American country to participate in the conference as they have close ties with Caribbean island countries by being a member of the Caribbean Community (commonly known as CARICOM). Figure 1 shows the location of the stations and Figure 2 shows how the number of stations changes with time.

[7] These data were subjected to a wide and fairly comprehensive variety of quality control tests similar to those described by *Peterson et al.* [1998a]. These tests include

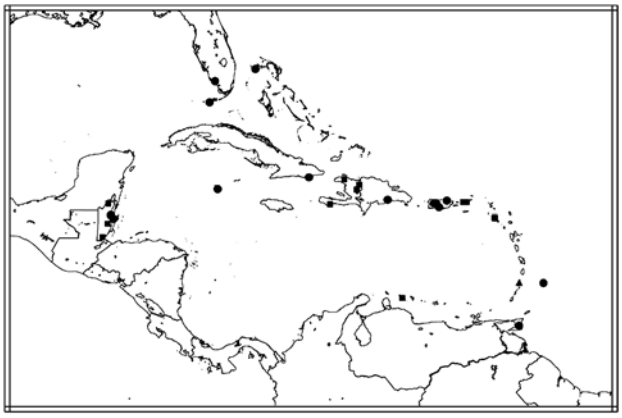

Figure 1. Locations of the 30 stations used in this analysis. Stations that provided both temperature and precipitation data are depicted by circles, stations with only precipitation data are shown by squares, and a triangle indicates the one station that provided only temperature data. Some stations are close enough to another one for their symbols to overlap. This is particularly true of the 3 stations in the Virgin Islands and the 4 stations in St. Kitts.

assessing the data for physically unreasonable values, unreasonably long consecutive occurrences of the same value, times when the daily maximum temperature was less than the minimum temperature, English to metric conversions problems, extreme outliers to the time series, and very long zero precipitation indicating that missing precipitation data was erroneously set to zero. Most of these problems were very rare. For example, the latter problem occurred in only two countries' data and had runs of such a long time with zero precipitation (e.g., 12 years) that they were easy to identify. Most of the other problems appeared to be digitizing errors where, for example, 28.2°C was digitized as 8.2°C.

[8] However, even correctly observed and digitized data may be unsuitable for long-term climate analyses. For

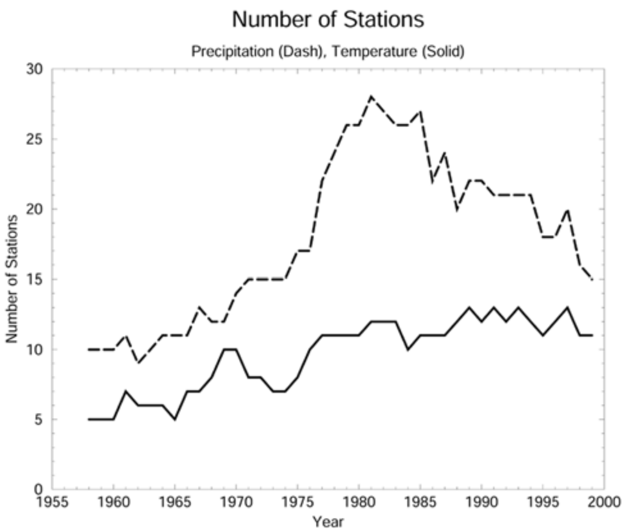

Figure 2. The number of stations versus time with temperature data in a solid line and precipitation data in a dashed line. The analysis uses data for the time period 1958 through 1999 and requires a minimum of 90% of the data for a station to be present for that year in order to contribute to that year's analysis or station count presented here.

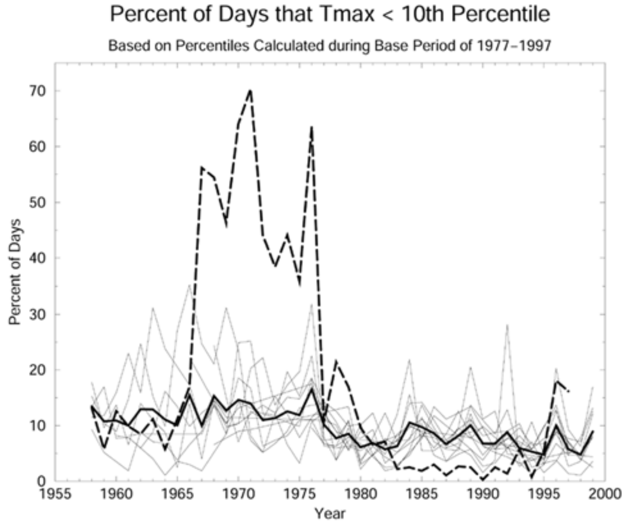

Figure 3. Example of detecting inhomogeneities in the data as determined by graphing an index, in this case the percent of day at or below the 10th percentile of maximum temperature. Maximum temperature data for Guantanamo Bay (heavy dashed line) were not used in the calculation of the mean time series (heavy solid line). The time series that contributed to the mean are shown in gray. While indices of extremes have considerable variability station to station, they generally indicate similar changes.

example, if a thermometer is moved from near the shade of a tree by the weather office to out in the grass near a tarmac, an artificial jump can occur in the time series [*Peterson et al.*, 1998b]. Our approach for dealing with inhomogeneities was to remove the most inhomogeneous observations from the analysis. Rather than run specific homogeneity tests, which generally focus on changes in mean values, each station's indices time series was evaluated for discontinuities and those with obvious discontinuities were not used in the regional analyses that use that observed variable (e.g., a problem in minimum temperature may not impact maximum temperature or precipitation observations). Figure 3 shows all the time series of the percent of the days with maximum temperature less than or equal to the 10th percentile. Two features are clear from examination of the figure. One is that indices of extremes show considerable variability from station to station. This is in agreement with the results of *Frich et al.* [2002]. The second is that one station, the U.S. station in Guantanamo Bay, Cuba, clearly has a discontinuity.

[9] As a result of the homogeneity assessments, two stations' minimum temperature and three stations' maximum temperature data were not used. All the precipitation data appeared homogeneous. This, too, is in agreement with other homogeneity assessments where the primary problem with precipitation homogeneity is associated with the effect that changes in the windshields have on solid precipitation catches [*Peterson et al.*, 1998b].

3. Methodology

3.1. Calculating Percentiles

[10] The exact methodology of calculating the indices is described on the KNMI indices web site. However, since

Table 2. Indices Calculated for the Caribbean Region

Index	Description
ETR	Intra-Annual Extreme Temperature Range
Tx90	Percent of Time Tmax ≥ 90th Percentile of Daily Maximum Temperature
Tn90	Percent of Time Tmin ≥ 90th Percentile of Daily Minimum Temperature
Tx10	Percent of Time Tmax ≤ 10th Percentile of Daily Maximum Temperature
Tn10	Percent of Time Tmin ≤ 10th Percentile of Daily Minimum Temperature
SDII	Simple Daily Intensity Index
R10	Number of days with Precipitation ≥ 10.0 mm/day
R5D	The Greatest 5-day Rainfall Total
R95T	Percent of Annual Total Rainfall due to Events Above the 95th Percentile
CDD	Maximum Number of Consecutive Dry Days

many of the indices are based on percentiles and there are several different valid approaches to calculating percentiles, the approach to percentiles used here needs explanation. Percentile thresholds for each station for each day are based on data from the period 1977 to 1997. The percentile exceedence thresholds for each calendar day are determined with respect to all observations during the base period within 2 calendar days of the individual day in question. For example, determining the 90th and 10th percentile of minimum temperature that would be applied to assess whether the minimum temperature at a station for March 15, 1961, was extreme, would be done by ranking all the daily minimum temperature observations from 1977 through 1997 from March 13 through March 17 and determining the 90th and 10th percentiles from those ranked data.

[11] Approaches to percentiles that are based on all the data only find warm extremes in the summer and cold extremes in the winter. That is not the case in the approach used here. Because the 90th percentile of maximum temperature is specific to the day of the year, the probability of exceeding it is the same during the entire year. In order for the analysis of a station to contribute to the results, 90% of the station's data had to be available for that year. All data for the base period 1977 through 1997 was used in the calculation of the percentiles, but not all years had to be present. For example, a station with 8 years of data during those base years would still be used in the analysis.

3.2. Area Averaging of Indices

[12] Not all indices calculated by *Frich et al.* [2002] or listed on the KNMI indices web site were relevant in the Caribbean. A most obvious irrelevant index is the number of days with minimum temperature at or below freezing. Other threshold indices also presented problems. Since the number of days that reach thresholds varies considerably from station to station, so does the standard deviation of the exceedences. Therefore, area averaging would be dominated by those observations with the greatest variance. Normalizing the variance would also present problems, as this would give considerable weight to a station that hardly ever exceeds the threshold value. Therefore, only one common threshold index's results will be presented.

[13] Since the stations are fairly well distributed around the region, regional averages presented are simply the numerical average of the index results from each station with data available to calculate the index. The indices based on percentiles evenly weight all stations in the area averages. However, other indices are not so evenly weighted. For example, some stations have more variability in the number of consecutive dry days or the greatest five-day rainfall total than other stations. In these cases, the simple area averaging approach can produce a representative time series only because the region is fairly small and the climate fairly homogeneous. As described in section 2, plots of every station's time series were made for each index as part of the homogeneity assessment. This analysis indicated that in no case was the area average dominated by the behavior of only one or two stations, though some stations did contribute more to the averaged signal than did others.

[14] The subset of indices calculated for the region is given in Table 2 and a longer description of each index will be presented when discussing the results of the analysis. Figures 4–11 show the averaged time series of the indices in Table 2. Also, a linear regression line is included in the figures to give a general sense of whether there is a trend present and whether the variance around the trend line is large or small. Due to the variability between one station and another, as shown in Figure 3, the value of the trends would be expected to change if an additional station or two were used in the analysis. Therefore, no numerical values of the slopes will be provided as that can imply a level of precision that the underlying data do not support. However, information on whether a linear regression line significantly represents the changes in the observations is provided.

4. Results

[15] The first index is the Intra-Annual Extreme Temperature Range (ETR). ETR is simply the warmest maximum temperature observation for the year minus the coldest minimum temperature observation. It provides some insight into the clear sky greenhouse effect, both natural and anthropogenic, because both the warmest maximum temper-

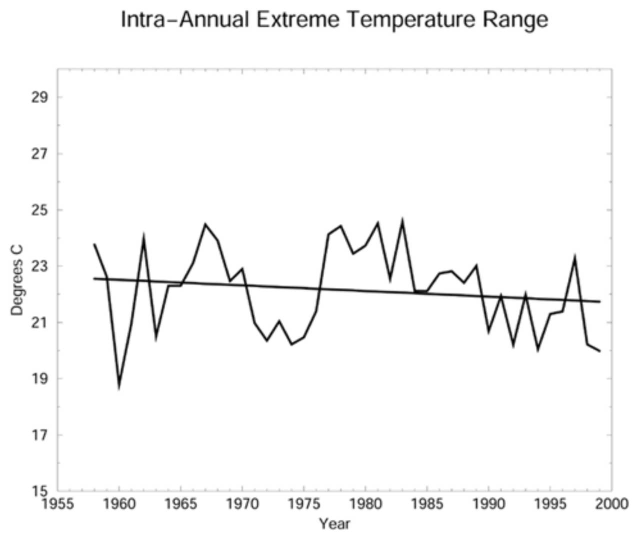

Figure 4. Mean area time series of the Intra-Annual Extreme Temperature Range (ETR) index. ETR is simply the warmest maximum temperature reading for the year minus the coldest minimum temperature.

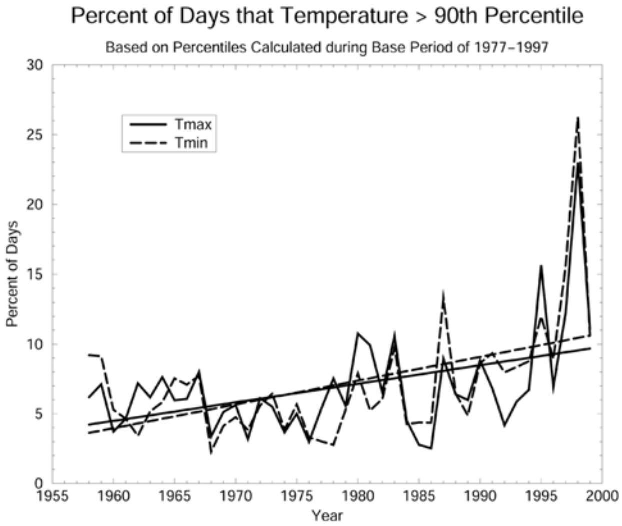

Figure 5. The percent of days maximum (solid line) and minimum (dashed line) temperatures are at or above the 90th percentile. Percentiles determined using data from 1977 through 1997.

ature and the coldest minimum temperature are likely to occur at the driest, most cloud free times. *Frich et al.* [2002] report, on average, a fairly steady decrease in ETR. As examination of Figure 4 indicates, ETR on average is decreasing slightly in the Caribbean basin, although the regression line is not significant at the 10% level.

[16] Changes in extremes of maximum and minimum temperature are shown in Figures 5 and 6. These figures show the percent of time that temperature observations are at or above the 90th percentile and at or below the 10th percentile. While much of the world reports greater warming in mean monthly minimum temperature than mean monthly maximum temperature [*Easterling et al.*, 1997], the Caribbean changes in maximum and minimum temperature extremes correspond closely to each other. The percent of time at or above the 90th percentile is increasing, with the last few years, particularly the strong El Niño year of 1998, reading quite high. By contrast, the percent of days at or below the 10th percentile has been decreasing, with the last few years, including 1998, not showing values much different than those earlier in the 1990s. All four linear regression slopes in Figures 5 and 6 are significant at the 1% level.

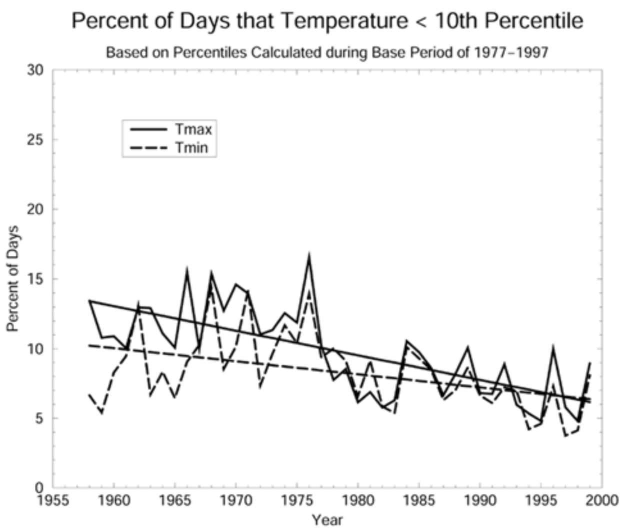

Figure 6. Percent of days when maximum temperature (solid line) or minimum temperature (dashed line) are less than or equal to the 10th percentile. Percentiles determined by data from 1977 through 1997.

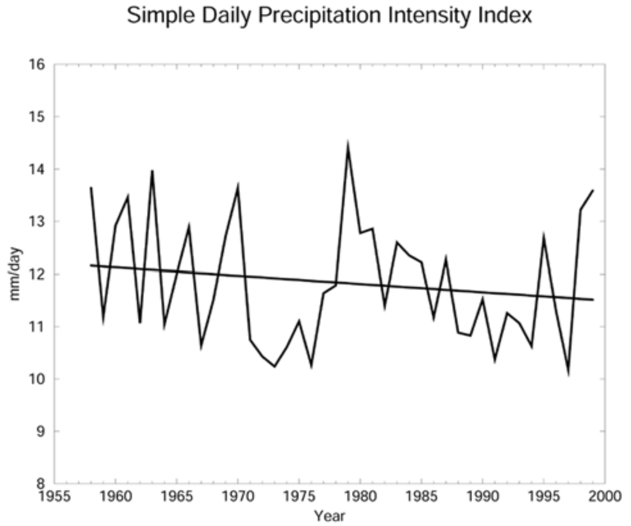

Figure 7. Mean Caribbean Simple Daily Intensity Index (SDII).

[17] The Simple Daily Precipitation Intensity Index (SDII) is simply the annual total precipitation divided by the total number of days with precipitation above a small threshold (Figure 7). This small threshold of $\geq$1.0 mm was used to prevent changes in the way a country deals with trace precipitation from impacting the results. The number of days with precipitation greater than or equal to 10 mm (R10) is very straightforward to calculate (Figure 8). Both of these indices reveal very similar behavior. While trend

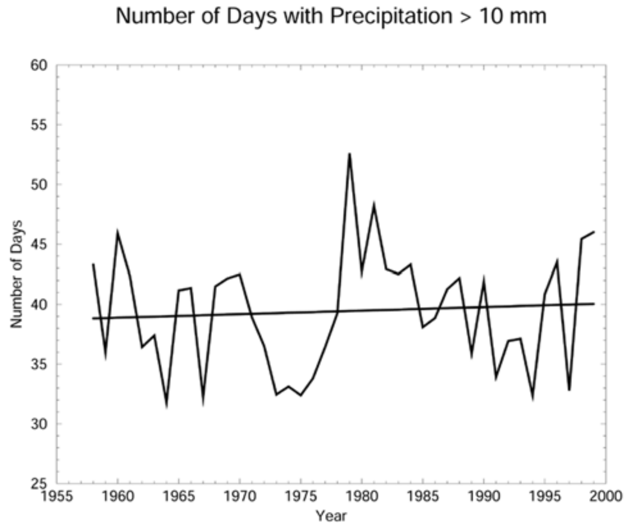

Figure 8. Mean number of days with precipitation greater than or equal to 10 mm (R10).

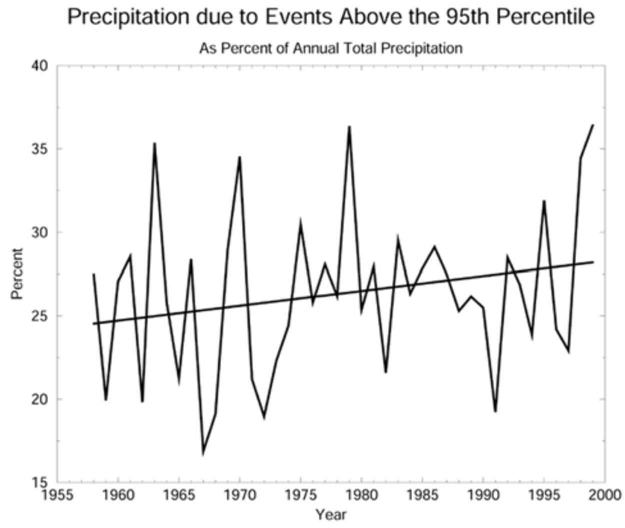

Figure 9. Mean percent of the total annual rainfall coming from events greater than or equal to the 95th percentile of daily precipitation (R95T). Percentiles based on data from 1977 to 1997.

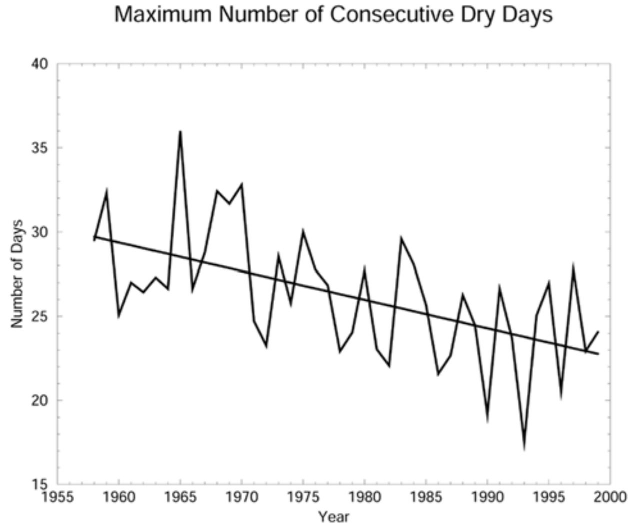

Figure 11. Mean regional maximum number of Consecutive Dry Days index (CDD).

lines for the entire period of record would indicate a decrease in SDII and an increase in R10, neither regression line is significant at even the 10% level as the dominant feature is that both indices are dominated by variability on the annual to decadal scales and that linear trends do not do a good job of representing the observed changes. While SDII is a measure of precipitation intensity, in this region of convective precipitation, the number of days with precipitation greater than or equal to 10 mm does not represent a measure of extreme precipitation. Instead, the number of days with precipitation over 10 mm in a region of tropical convection is likely to be strongly related to the number of days with precipitation.

[18] One measure of extreme precipitation is the percentage of total precipitation due to events above the 95th percentile (R95T). Examination of extreme precipitation indicates that, to a first approximation, heavy rainfall is increasing where precipitation is increasing and decreasing where precipitation is decreasing [*Groisman et al.*, 1999]. Therefore, index R95T is normalized by the total annual precipitation. Examination of Figure 9 indicates that R95T tends to be increasing, but the regression slope is not significant at the 10% level as there is considerable interannual variability. Another measure of extreme precipitation is the greatest 5-day rainfall total (R5D, Figure 10). Often the heavy rains that induce flooding occur over the course of several days and should be captured by this index. R5D is also increasing (significant at the 10% level) but with considerable variability.

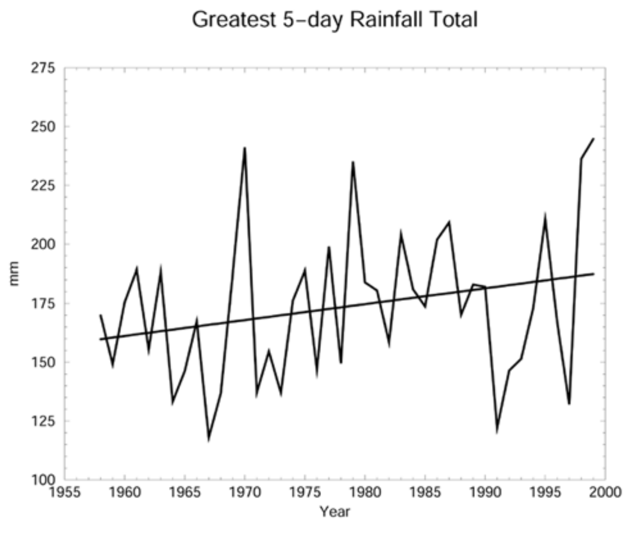

Figure 10. Mean index of the greatest annual 5 day rainfall total (R5D).

[19] As precipitation is zero bounded, assessing extremes of low precipitation is a different challenge. One index that somewhat addresses this is the annual maximum number of consecutive dry days (CDD). A dry day is defined as one where precipitation is less than 1 mm. As examination of Figure 11 indicates, CDD is decreasing in the region with the linear slope significant at the 1% level. The strong El Niño year of 1998 does not stand out as unique in any of these indices of precipitation.

5. Discussion

[20] While tropical storms obviously have a direct impact on precipitation indices, in general, the number of tropical storms [*Neumann et al.*, 1987] or intense tropical storms [*Landsea*, 1993] in the Atlantic is only weakly correlated with any of the precipitation indices. The two most highly correlated indices, SDII and R95T, when compared to the number of intense hurricanes in the Atlantic have r of 0.41 and 0.42, and their relationship with the number of named storms in the Atlantic is even weaker.

[21] Several of the precipitation indices, particularly the SDII, R10, and R95T, which have insignificant trends, are dominated by variability on annual and decadal-scales. This variability, particularly the strong decadal signal where the Caribbean is dry in the early 1970s and late 1980s to early 1990s, and wet in the late 1960s and early 1980s, is

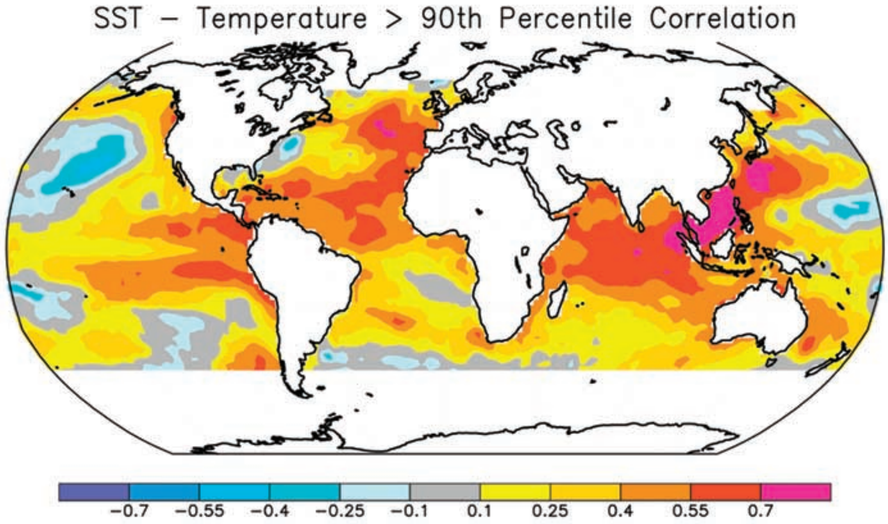

Figure 12. Correlation (r) of SSTs with index of the percent of days with temperature at or above 90th percentile (the mean of Tx90 and Tn90). Removing 1998, the year with an extremely high value for the index, from the correlation analysis gives the same pattern but with somewhat weaker correlations. SST correlations with the percent of days with temperature below the 10th percentile has a remarkably similar pattern but with correlations of the opposite sign and a little weaker.

consistent with that seen in other analyses of variability of Caribbean precipitation [e.g., *Taylor et al*., 2002].

[22] Sea Surface Temperatures (SST) could also be expected to be closely related to some of the changes seen in daily data. Therefore, an analysis was done comparing time series of the different Caribbean region indices with global SSTs. The historical SST data used were reconstructed using empirical orthogonal functions and have data from 1950 to the present [*Smith et al.*, 1996]. Figure 12 shows the correlation (r) of global SSTs to a time series of the percent of days that temperature is greater than or equal to the 90th percentile (the average of Tx90 and Tn90). As one might expect, exceeding the 90th percentile is related to warmer SSTs in the Caribbean basin. However, local SSTs only explain about 25% of the variance of extremely high temperatures.

[23] Figure 12 also shows a positive relationship to SSTs in the eastern Pacific Ocean. When the extremely high value in the T90s time series corresponding with the 1997–1998 El Niño is removed from the time series, the pattern doesn't particularly change although the correlations are lower. In distant regions such as the Indian Ocean or the South China Sea, the positive correlation may be largely due to similar underlying trends. Analysis of SST correlations with a time series of the percent of days with temperature less than or equal to the 10th percentile reveals essentially the same pattern as that shown in Figure 12 except the correlations have the opposite sign and are slightly weaker.

[24] Of the precipitation indices, SDII shows the strongest relationship with SSTs. As shown in Figure 13, SDII is most closely related to SSTs in the southern Caribbean Sea and, to a lesser extent, those of the whole tropical North Atlantic

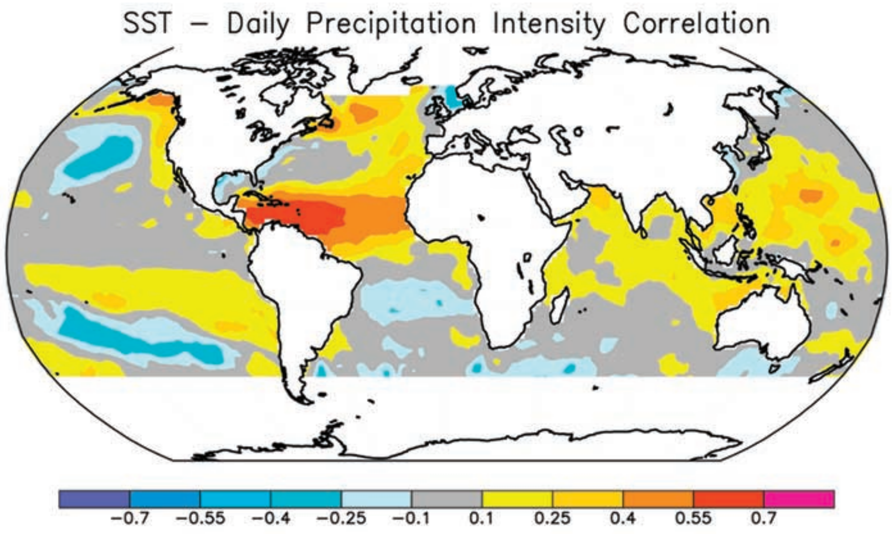

Figure 13. Correlation (r) of SSTs with mean Simple Daily Intensity Index (SDI).

Ocean. This makes physical sense as the trade winds blowing over warmer waters should have more moisture available to precipitate. The number of days with rainfall greater than or equal to 10 mm also shows a similar relationship to SSTs while measures of extreme precipitation, R5D and R95T have correlations (r) with the SSTs in the Caribbean Sea and tropical North Atlantic of only 0.3 to 0.5. Some indices, such as CDD and ETR, show little if any relationship with even local SSTs.

[25] Only in the time series of Tx90 and Tn90 does the strong El Niño year 1998 stand out as unusual. None of the annual precipitation indices show strong relationships with El Niño. This result with annual analysis is not surprising because other research has shown that the nature of the relationship between Caribbean precipitation and El Niño changes character through the course of the year. That is, early in the year at the beginning of the Caribbean rainfall season (May–June), correlations tend to be positive between the Caribbean precipitation and Equatorial Pacific SST Anomalies (SSTAs), with the most significant correlations involving a lag of 4–6 months. Later in the rainfall season however, (August–September) the correlations are negative (though weaker) and best for concurrent Pacific SST anomalies [*Giannini et al.*, 2000; *Chen and Taylor*, 2002].

[26] *Frich et al.* [2002] report that on a "globally" averaged basis since the early 1950s, ETR is decreasing, Tn90 is increasing, SDII is increasing, R10 is increasing, measures of extreme precipitation, R5D and R95T are both increasing, and CDD is decreasing. The Caribbean results agree with the "global" averages for the indices relating to temperature and extreme precipitation — both heavy precipitation and length of dry spells. However, unlike the "global" average, the Caribbean region does not show an increase in SDII over this time period.

6. Conclusion

[27] Several insights were gained through this analysis. One is that the climate of the Caribbean region is changing. The extreme intra-annual temperature range is decreasing. The number of very warm days and nights is increasing dramatically while the number of very cool days and nights are decreasing. The maximum number of consecutive dry days is decreasing and the number of heavy rainfall events is increasing. These changes are similar to those reported from "global" analysis [*Frich et al.*, 2002]. Indices of some of these variables show relationships with hurricanes and sea surface temperatures, but no one factor dominates all the observed changes.

[28] In the process of creating this analysis, insights into the value of digital records of daily weather were gained. As a result, increased efforts are underway in several Caribbean countries to digitize available paper archives. Indeed, some of the station time series used in this analysis were prepared immediately after the workshop. Also, it became clear that these derived indices as well as the original daily data have considerable value to a wide variety of research. Therefore, the complete time series of the indices presented here will be made available through the University of the West Indies Department of Physics' web site (http://wwwphysics.uwimona.edu.jm:1104). In addition, all the daily data used in this analysis is being made available to researchers. This compilation of Caribbean region data will be supplemented with additional time series as data from more stations are digitized. To obtain a copy of the data for research purposes, please contact M. Taylor (mataylor@uwimona.edu.jm).

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