Long-term trends in precipitation and temperature across the Caribbean

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Abstract

This study considers long-term precipitation and temperature variability across the Caribbean using two gridded datasets (CRU TS 3.21 and GPCCv5). We look at trends across four different regions (Northern, Eastern, Southern and Western), for three different seasons (May to July, August to October and November to April) and for three different periods (1901-2012, 1951-2012 and 1979-2012). There are no century-long trends in precipitation in either dataset, although all regions (with the exception of the Northern Caribbean) show decade-long periods of wetter or drier conditions. The most significant of these is for the Southern Caribbean region which was wetter than the 1961-90 average from 1940-1956 and then drier from 1957 to 1965. Temperature in contrast shows statistically-significant warming everywhere for the periods 1901-2012, 1951-2012 and for over half the area during 1979-2012. Data availability is a limiting issue over much of the region and we also discuss the reliability of the series we use in the context of what is known to be available in the CRU TS 3.21 dataset. More station data have been collected but have either not been fully digitized yet or not made freely available both within and beyond the region.

1. Introduction

The climatology of the Caribbean region has been less well studied than the North American continent situated to its north. This is partly due to less of the historic climatic data being digitally available, but also due to the region being composed of many small independent countries, some just encompassing one or a few small islands. Early analyses consider monthly precipitation series from individual islands (e.g. Kraus, 1955, Granger, 1985 and Singh, 1997a) or as parts of studies comparing Caribbean averages (often including parts or all of Central America) with other regions of the tropics. Hastenrath (1976, 1978 and 1984) has been the early proponent of such work showing that the Caribbean-Central American region (as characterised by a 48-station average) is inversely related with precipitation averages from the Great Plains in the United States and also with rainfall and sea-surface temperatures (SSTs) along the Peruvian and Ecuadorian coast. Hastenrath's work also emphasized links between their regional rainfall series and SSTs and wind and pressure patterns over the Tropical Atlantic.

Hastenrath and Polzin (2013) reassessed the early work, using the same 48-station average, but only updating the series to 1986. The work also updated the wider regional links using many of the atmospheric and ocean circulation indices that have been more widely used since the 1980s [e.g. indices of the El Niño/Southern Oscillation (ENSO) phenomenon, the North Atlantic Oscillation (NAO) and tropical Atlantic SSTs]. Many papers in the last 15 years have assessed the same issues, looking at links between the tropical Atlantic and Pacific SSTs and Caribbean/Central American rainfall (Enfield and Alfaro, 1999, Giannini et al., 2000, Chen and Taylor, 2002, Spence et al., 2004 and Stephenson et al., 2007), generally with the aims of understanding regional dynamical drivers and identifying possible seasonal forecasting potential. These papers used gridded precipitation products which combine *in situ* measurements with satellite products, but there has been little discussion of longer timescale trends across the region. One of the datasets used in some of these analyses was developed by Magaña et al. (1999) for the period 1958 to 1995 (at a resolution of 1° by 1° latitude/longitude resolution), where the construction is also extensively discussed by Taylor et al. (2002). Although this dataset uses many stations, the vast majority are from Central America (see Figure 2 of Taylor et al., 2002).

Reverting to the large-scale Hastenrath type of work looking at the greater Caribbean region, Jury (2009a, b) and Jury and Gouirand (2011) attempted to determine the strength of any interdecadal, quasi-decadal and decadal scale variability across the Caribbean using earlier versions of the gridded datasets we will use in this paper (see next section). These gridded products are based solely on *in situ* records and our aim is to focus on these specifically for the Caribbean region.

The basic climatology of the region has been described in a number of earlier works (e.g. the earlier works of Hastenrath previously mentioned) and more recently by Taylor and Alfaro (2005). Many studies (e.g. Chen and Taylor, 2002 and Spence et al. 2004) discuss the regional climatology in terms of a wet season (June to November) which coincides with the period of hurricane passage across the region. The aims of this paper are more along the lines of Jury's work, addressing both the issue of whether long-term changes are identifiable in seasonal temperature and precipitation amounts across the region and whether the changes are specific to sub-regions or occur with similar timing across the entire Caribbean. Our paper, then, builds on further work by Jury (2009c) and also to a lesser extent on the seasonal and regional definitions from Jury et al. (2007), which in turn were based on factor analyses of the annual cycle initiated by Giannini et al. (2000). The latter type of analysis is somewhat non-standard and was chosen to cope with the often relatively short duration records, where a common period of measurements across many sites was impossible to develop. More recently, a few studies have begun to consider climate change in the coming decades on Caribbean wide and sub-regional scales using global and regional climate model simulations (e.g. Singh 1997a, b, Angeles et al., 2006, Neelin et al., 2006, Campbell et al., 2010, Charlery and Nurse, 2010 and Hall et al. 2012). Additionally, Pérez and Jury (2013) have looked at long-term changes for Hispaniola in the context of future simulations by climate models. Karmalkar et al. (2013) have also defined two Caribbean regions (western and eastern), but this was primarily for comparing with simulations from the PRECIS Regional Climate Model at 50km resolution.

The purpose of this paper is to consider sub-regions of the Caribbean in a longer-term context (back to the beginning of the 20th century) using recently-enhanced gridded datasets. We will refer to earlier work in the discussion of the spatial patterns of observed change and in regional time series of precipitation and temperature across the region. The emphasis is on seasonal timescale changes from data of monthly totals and averages. Because data availability is such a significant issue within the region, a great deal of emphasis is also placed on the examination of the datasets used (e.g. coverage and coherency) in the context of the discussion of the trends they reflect. Changes in daily precipitation and temperature extremes have been considered by Peterson et al. (2002), Stephenson et al. (2014) and Mclean et al. (2015) and this timescale is not considered here. This paper is structured as follows. The various datasets used are introduced in section 2. Section 3 defines the seasons used and sub-regional definitions before describing analyses derived from the datasets in terms of time series plots and spatial patterns of trends. Discussion follows in section 4 with some conclusions in section 5.

2. Datasets used

In this assessment of long-term trends across the Caribbean, we make use of gridded datasets of observational station data (CRU TS 3.21, Harris et al., 2014 and GPCCv5, Becker et al., 2013, developed respectively by the Climatic Research Unit, CRU at the University of East Anglia, UK and the Global Precipitation Climatology Centre, GPCC at Deutscher Wetterdienst in Germany). Precipitation data are included in both datasets, but temperature only in CRU TS 3.21. Recently-developed extended Reanalyses (20CR, Compo et al., 2011 and ERA-20C, Poli et al., 2013 and Hersbach et al., 2015) are potentially useful data products for this type of study, but are not considered here. With our emphasis on precipitation, even the ERA-Interim Reanalysis (Dee et al., 2011) from 1979 are not adequate, as many of the smaller Caribbean islands are not represented as land as the resolution is only 0.7° by 0.7° of latitude/longitude (approximately 80km). The extended Reanalyses have the same resolution issues. Further downscaling to finer scales (e.g. ERA-20C/Land, which downscales to 25km but has yet to be released) may provide more useful data series, but their use would need extensive validation. Early papers (Granger, 1985 and Singh, 1997a, b) comment on the strong precipitation gradients across some islands (from the windward to the leeward side) but if the islands are not even represented then doubt must be cast on the veracity of the data recent Reanalyses produce.

Jury et al. (2009c) intercompared earlier versions of CRU TS 3.21 and GPCC with numerous Global Climate Model simulations and Global and Regional Reanalyses using a network of rain gauges from Cuba to Barbados. This study considered how well the various datasets reproduced the spatial patterns and seasonal cycle for a climatological average for the period 1979-1990. The two products we will use performed well in western parts of the Caribbean, but the earlier version of CRU TS 3.21 (CRU TS 2.1) used by Jury et al. (2009c) was perceived to be too wet over the eastern islands of the Lesser Antilles.

The quality of any observational-based gridded product is clearly dependent on the number of station observations that are available. We make use of the station availability through time used in the CRU TS 3.21 dataset as one means of assessing quality, with a second means being the degree of agreement between the same variable measured by the two data products. For GPCCv5, information on the specific station data used are not provided with the dataset. GPCC just release gridded products at the same resolution as CRU TS 3.21. Figures 1 and 2 show the locations of the CRU TS 3.21 precipitation and temperature measuring sites, respectively, for the 1951-2012 period. We map this for a larger spatial domain than used in this study and show the locations of the sites. In these figures, an infilled circle means that the site has at least 50% of the monthly values for this 62-year period and an unfilled circle has less than 50% of the time series with monthly values. In general, there are slightly more precipitation than temperature series. The precipitation map (Figure 1) shows similar numbers of stations to the Magaña et al. (1999) dataset (see Figure 2 of Taylor et al., 2002) for the Caribbean, but fewer series over Central America, particularly for Nicaragua.

In the development of the CRU TS 3.21 dataset (Harris et al., 2014) the high-resolution grids use a search radius (1200km for temperature and 450km for precipitation). GPCCv5 (Becker at al., 2013) use a comparable search radius for precipitation which is 3.5° of latitude and longitude at the Equator, which reduces for higher latitudes according to the cosine of latitude. For Caribbean latitudes this is also about 450km. So precipitation grids across Guyana and Suriname, for example, will use data from within these countries, but will additionally be informed by data from eastern Venezuela and northern Brazil. Similarly the northern Caribbean region will make use of longer and more complete series from Florida to the north and Belize will be influenced by Mexican data to the west and Honduran series to the south. Data density across most of the region is, however, poor and could be markedly improved by digitizing and making available more of the data that have been collected, particularly for years before independence. The implication of this is that with a spatial resolution of 0.5° by 0.5° latitude/longitude degrees, the gridded products will reuse many stations to develop all the grid-box series, more so for temperature than precipitation (see Figures 1 and 2 and Harris et al., 2014). Due to the greater spatial coherency of temperature compared to precipitation variability (i.e. greater correlation between sites for the same separation), we would intuitively expect there to be better agreement between these datasets for temperature changes at the regional scale than for precipitation. Additionally, the numbers of stations with digitized data for the region in CRU TS 3.21 improves dramatically for the periods from 1951 or 1961 than for the first half of the 20th century. For a station to be used within CRU TS3.21 sufficient data are required for the variable to be expressed as an anomaly/percent anomaly (for temperature/precipitation) from the 1961-90 base period. Station availability for this period is therefore better than any other period, but the fact that there are more stations available then should not affect results for the overall period (1901-2012). Interpolation using anomalies or percent anomalies will not lead to a bias. The GPCCv5 interpolation method is much more complex (Becker et al. 2013) and the apparent bias in these data before 1920 could be a result of this. Without knowing which specific stations were used by GPCCv5 precludes further study of this. The use of more than one dataset, where this is possible, allows potential problems in one of the datasets to be illustrated.

3. Analyses

Jury et al. (2007) derived four clusters of coherently-varying precipitation variability from the Northern Caribbean. Their analysis extended from Cuba in the west and Bahamas in the north to the northern islands of the Lesser Antilles in the east and south. Our Caribbean region is more extensive encompassing all the above, but also the rest of the Lesser Antilles, Guyana, Suriname and Belize (see Figure 3 and also Figures 1 and 2). With respect to the sub-regional definitions shown on this map they are purely determined geopolitically as opposed to being strictly climatic. The northern region in Figure 3 encompasses three of the four regions proposed by Jury et al. (2007). Belize to the west and Trinidad and Tobago and Guyana and Suriname to the southeast are clearly two distinct regions separated from the principal Caribbean island chain.

As well as presenting plots of time series averages for sub regions, we additionally have developed trend maps of change in precipitation and temperature for three periods (1901-2012, 1951-2012 and 1979-2012). These were chosen as the full period of availability of gridded observational products, the period of enhanced observational coverage (1951-2012) and the most recent period with extensive satellite- based coverage and reanalysis products (1979-2012, see also Jury, 2009c).

The main feature of precipitation over the Caribbean is a well-defined annual cycle. Taylor and Alfaro (2005) and Jury (2009c) show that for most of the region (Belize and the Islands of the Caribbean Sea), this cycle is characterised by maximum precipitation from May to November and a dry period peaking in February–March. Particularly in the northwest of the Caribbean, the wet season tends to be bimodal with peaks in May–June (early season) and August–October (late season). In the southeast of this Caribbean region (particularly Guyana and Suriname) the bimodal peaks are May to July with a lesser one in December and January. These peaks are separated by a reduced rainfall period (July-August) called the mid-summer drought/dry spell in Central America/Caribbean, respectively (Magaña et al. 1999, Gamble and Curtis 2008 and Gamble et al., 2008). The relative minimum in rainfall tends to be a month later (August-September) over Trinidad and Tobago and September and October for Guyana and Suriname. The term 'mid-summer drought' is more widely used in Central America, where the reduction is more marked than in the Caribbean.

Figures 4-7 show time series plots for the four regions of precipitation totals from the CRU TS 3.21 dataset for the three seasons (May, June and July: MJJ; August, September and October: ASO; and, November to April: NDJFMA) and the calendar year totals (ANN) as anomalies from the 1961-90 reference period. The first two three-month seasons represent the early and late wet seasons (after Taylor et al., 2002) who suggest different driving mechanisms for the respective periods. The third season is representative of the dry season everywhere except the southern Caribbean. In all plots we show a 10-year Gaussian smoothed series to highlight longer-term variations. Additionally, on each plot, we show the similarly smoothed time series produced by GPCCv5. For each annual plot we indicate the number of precipitation gauges used in the grid-box interpolation for each region for the CRU TS 3.21 dataset. The number of stations available to the gridded product varies considerably during the course of period from 1901 to 2012. Numbers are markedly lower before 1951 and are also lower in the recent two decades, particularly for the Northern Caribbean region for precipitation in Figure 4. As expected, station coverage is lower for the smaller-sized eastern and western regions. For these two regions, coverage reduces to zero for some years before 1940. Thus here, the series will be composed of interpolated values from stations outside the region, but still within the 450km limit.

Table 1 gives the monthly average values for both datasets for the 1961-90 climatological base period. The values here represent the simple averages of all 0.5° by 0.5° latitude/longitude squares that contain land within each region. The timings of the relative minima in rainfall (discussed earlier in this section) are highlighted for three of the four regions in Table 1. Table 2 gives correlations between the two datasets for three periods (1901-2009, 1921-2009, 1951-2009 and 1979-2009) for the three selected seasons and the annual total. The final year here is determined by the availability of GPCCv5, which finishes in 2009. In Figure 8 we plot CRU TS 3.21 temperature change (as anomalies from 1961-90) over the period from 1901 for all four Caribbean regions. Here we just plot the time series for the calendar year average. Station availability for temperature is lower than for precipitation, as is also evident when comparing Figure 2 with Figure 1. Station availability within the regions drops to zero for three of the regions, so the data are infilled from further afield - for temperature stations up to 1200km have been used compared with up to 450km for precipitation (see the discussion of the gridded datasets in Section 2).

The time series trends looked at the four regions individually. We will now look at spatial patterns across the Caribbean region to see if anything has been missed by looking at the four sub-regions. With the basic datasets (CRU TS 3.21 and GPCCv5) being gridded datasets at a 0.5° by 0.5° latitude/longitude for land areas, we can plot precipitation trend maps for the 1979-2012 period for each of the three seasons for CRU TS 3.21 (Figures 9-11) and 1979-2009 for GPCCv5 (Figures 12-14). We highlight regions where the trend is statistically significant. Finally, we plot a similar trend analyses for annual mean temperature for the 1979-2012 period for CRU TS 3.21 in Figure 15.

4. Results and Discussion

The emphasis in this section is mostly on the precipitation changes which are more variable across the region and over time, with the more consistent temperature variations mentioned briefly at the end. Figures 4 to 7 show time series for the three selected seasons together with annual totals, with each Figure showing all four series for each of the Caribbean sub-regions. Each plot expresses the precipitation as mm anomalies from the 1961-90 base period. The different sizes of the regions, with the Northern one being by far the largest, need to be borne in mind when interpreting the results.

The agreement between the two datasets (CRU TS 3.21 and GPCCv5) is generally good (see the correlations in Table 2), but these correlations are not as high as in more data dense regions further north in North America and also in Europe (Harris et al., 2014). GPCCv5 series tend to show higher precipitation totals for periods before about 1920 for all four regions except the Southern Caribbean. For the small Eastern Caribbean region, GPCCv5 gives higher precipitation anomalies before 1920 but lower anomaly values since the 1990s. Also for the Western Caribbean region, GPCCv5 gives higher precipitation anomalies before 1950.

The regional precipitation averages for the base period of 1961-90 are given in Table 1. GPCCv5 regions tend to be drier in an absolute sense, particularly so for the Eastern Caribbean region (about 25% lower), an observation commented upon by Jury (2009c). The limited number of gauges in this region (see Figure 1) influences the CRU TS 3.21 dataset as year-to-year variability for all seasons reduces dramatically before about 1930, caused by the interpolation then using more distant gauges. Differences between datasets are much smaller for the other regions and are negligible for the Western Caribbean. For all four sub-regions, the seasonal cycle is similar for both gridded products (Table 1).

Table 2 gives correlations for the three seasons and annual totals between the CRU TS 3.21 and GPCCv5 datasets over four time periods (1901-2009, 1921-2009, 1951-2009 and 1979-2009). Correlations between the two datasets for the same region are all statistically significant, but are markedly reduced for some of the seasons for the Eastern and Western Caribbean, particularly those involving the 1901-1920 period. These reductions are due to the greater differences between the two datasets, with GPCCv5 tending to show unrealistically high levels during these twenty years (see especially Figures 5 and 7). To allow for this this, we additionally give correlations for the 1921-2009 period in Table 2. Despite the correlations being reduced in earlier periods, possibly due to the regional series being based on fewer stations, the correlations between the two datasets are still highly statistically significant. Inter-regional correlations are not that large but tend to be greater when involving the larger Northern Caribbean region. Correlations with the Southern Caribbean region are much weaker, as this region doesn’t share the similar mechanisms that drive rainfall amounts in the other three Caribbean regions (see Taylor et al. 2002). The inter-regional correlations are higher for the two wetter season periods of May to July and August to September than for the November to April season or the annual totals.

One of the main results is that neither precipitation dataset shows any statistically significant century-scale trends across the region. Decadal-scale variability is more apparent in the smaller sub-regions, with the larger Northern region showing the least. Apart from the Eastern region, the timing of the variability is similar between sub-regions, strongly suggestive of being influenced by SST variability (as previously discussed by Enfield and Alfaro, 1999, Chen and Taylor, 2002 and Taylor et al., 2002). The wetter (1931-38 and 1950-56) and drier (1939-47 and 1971-78) periods noted by Hastenrath and Polzin (2013) for the Caribbean are difficult to see across the four sub-regions but are not entirely absent. For example, the 1970s drying is evident in the annual plots for the Northern, Eastern and Western Caribbean (Figures 4, 5 and 7). It is also noted that the 1940s were dry over the Western Caribbean (Figure 7), while the main feature of any of the regions occurs in the Southern Caribbean (Figure 6) with a wet phase from 1940 to 1956 followed by a drier phase from 1957 to 1965, by far the biggest fluctuation in all four annual series. Other studies (e.g. Peterson et al. 2002 and Taylor et al. 2002) similarly identify strong decadal variability in Caribbean rainfall manifesting in an anomalously dry Caribbean in the early 1970s and late 1980s to early 1990s and a wet Caribbean in the late 1960s. While not quite consistent across all plots, most of the plots capture the shift towards wetter conditions after the early 1990s.

As is also common with precipitation variations in many regions of the world, some of the seasonal and regional time series are positively skewed, i.e. the positive anomalies tend to be slightly larger than the negative departures. The Northern (Figure 4) and Eastern (Figure 5) Caribbean sub-regions tend to show higher precipitation totals since about 2000, but again it is noted that overall none of the sub-regional-average series shows century-timescale trends. The main features are periods of about a decade in length which were wetter or drier than the 1961-90 base period in all Caribbean regions, but the amplitude is markedly reduced in the larger northern region.

Figures 9 to 11 (for CRU TS 3.21) and Figures 12 to 14 (for GPCCv5) show plots of spatial precipitation trends for the three seasons for the period 1979 to 2012 (2009 for GPCCv5). Few of the regions show any trends that are statistically significant at the 95% level. This also applies (not shown) to the two longer periods (1901-2012/2009 and 1951-2012/2009). The significant drying seen in the Bahamas for the NDJFMA season during 1979-2012 for CRU TS 3.21 (Figure 11) is also evident in the GPCCv5 data (Figure 14) but is less spatially extensive. Longer-term trends towards drying are evident for 1901-2009 for GPCCv5, but for this dataset, the first 20 years of the 20th century are generally unrealistically too wet (e.g. Figures 4, 5 and 7). As GPCC doesn't provide access to the underlying station series, it is impossible to determine why GPCCv5 shows this feature.

Figure 8 which shows annual temperature averages for the four Caribbean regions indicates strong warming across all regions, particularly since the 1970s. The only earlier decades warmer than the 1970s were the 1960s for the Northern Caribbean, the 1950s for the Western Caribbean and the 1940s for the Eastern and Southern Caribbean. Only temperature trends are shown for the annual average for the period since 1979-2012 in Figure 15. Most regions show statistically significant warming except for the eastern half of the Northern Caribbean (eastern Cuba and Haiti), northern parts of the Southern Caribbean (northern Guyana) and western parts of the Eastern Caribbean (Puerto Rico). For the two longer periods almost every location shows statistically significant warming for the 1901-2012 and 1951-2012 periods. The annual temperature cycle across the Caribbean (see Table 1) is reduced in the Eastern and more especially in the Southern region compared to the other two as they are more equatorward and, in the Eastern case, more maritime.

5. Conclusions

Seasonal precipitation totals for four sub-regions of the Caribbean, estimated using two gridded datasets, reveal no century-scale trends, but there are periods of up to ten years when some regions were drier or wetter than the long-term average. The greatest such fluctuation seen was in the Southern Caribbean which was wetter than the 1961-90 average from 1940-1956 and then drier from 1957 to 1965. Only a few small parts of the Caribbean exhibit statistically significant precipitation trends over the recent 1979-2012 period. In contrast to precipitation, much of the Caribbean region shows statistically significant warming over the same period and this applies to all the regions for the 1901-2012 and 1951-2012 periods, but only about half of the region for 1979-2012. Temperature change for this latter period is not significant over eastern Cuba, Jamaica, Hispaniola, Puerto Rico and the northern half of Guyana and Suriname.

Agreement between the two precipitation datasets (CRU TS 3.21, Harris et al., 2014 and GPCCv5, Becker et al., 2013) is generally good, except for the Eastern Caribbean region. Here GPCCv5 suggests a decrease in precipitation since the 1990s compared to CRU TS 3.21. Also for this region, CRU TS 3.21 is about 25% wetter than GPCCv5 in an absolute sense. GPCCv5 appears to be excessively wet in all regions prior to about 1920. Nonetheless, the reasonable agreement between the datasets bolsters the idea that the century-long lack of a trend in precipitation is real notwithstanding the sparse data available. This study suggests a need to further investigate why, with a positive trend in surface temperatures, there has been no significant trend in precipitation, especially as precipitation in the region is strongly linked to surface temperatures. The question is why ‘warmer’ has not translated into ‘wetter’. Peterson et al. (2002) suggest that interannual variability currently dominates the precipitation signal and likely accounts for the lack of an overall trend. There may be a regional trend toward increased high frequency precipitation variability as a result of a global warming signal, for example due to the increased frequency of occurrence of ENSO events (Trenberth and Hoar, 1996) which are known drivers of Caribbean rainfall (e.g. Taylor et al., 2002). Several recent modelling studies (e.g. Taylor et al., 2011, 2013; Rauscher et al., 2011; Karmalkar et al., 2013; Fuentes-Franco et al., 2015) indicate that SST warming in the Caribbean will lead to drying in the Caribbean and Central America in future decades (often more distant periods such as the 2071-2100 period). Our study supports the need for further investigation, but with a greater emphasis on observational data.

Finally, this study highlights that the availability and completeness of many of the underlying station series for the region is poor, especially when compared to the North American continent situated to the north. Long-term records have been collected, but for many of the countries of the region they remain to be both completely digitized and made freely available. Further evidence for this conclusion comes from the more extensive daily datasets used to assess whether changes in extremes are occurring across the region (Stephenson et al., 2014), for which some of the station data hasn't been released. We encourage more of the Meteorological Services in the region to make their digitized data more available, and to expand ongoing data rescue activities to include data collected before many of the island nations became independent.

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Tables

Table 1: Monthly average Precipitation amounts (mm) and monthly average Temperature (°C) over the 1961-90 climatological period for the four Caribbean regions (Figure 3) and the two gridded datasets (CRUTS is CRU TS 3.21 and GPCC is GPCCv5) used in this study. The driest months in the May to October period are emboldened for all regions except the Eastern.

Prec.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CRUTS N	59.2	55.8	57.9	91.8	188.7	166.2	**130.4**	159.0	182.8	171.2	104.6	69.0
GPCC N	52.6	51.1	53.3	82.4	169.7	153.5	**112.4**	143.5	166.2	178.7	96.4	60.6
CRUTS E	148.8	110.0	105.8	148.6	198.2	196.7	224.2	248.3	258.3	274.3	282.9	199.5
GPCC E	106.7	71.6	77.3	95.6	126.8	143.2	183.9	209.7	219.2	209.7	216.2	146.7
CRUTS S	200.0	145.0	174.0	222.4	345.0	334.3	270.7	186.6	98.2	**87.7**	111.4	184.9
GPCC S	174.9	121.7	145.0	195.1	316.4	324.6	256.5	178.7	96.8	**81.3**	112.1	171.5
CRUTS W	133.7	71.6	55.8	60.1	137.7	267.0	295.9	**246.7**	294.7	262.9	199.2	164.2
GPCC W	126.8	71.9	58.6	51.5	116.0	300.0	296.0	**275.5**	297.2	245.4	184.4	153.8
Temp.												
CRUTS N	22.3	22.6	23.6	24.6	25.7	26.6	27.1	27.2	26.8	26.0	24.6	23.1
CRUTS E	24.0	24.0	24.4	25.0	25.8	26.3	26.3	26.5	26.4	26.1	26.0	24.7
CRUTS S	25.2	25.2	25.6	25.9	25.9	25.6	25.6	26.0	26.6	26.8	26.6	25.7
CRUTS W	22.7	23.3	24.8	26.2	27.1	27.1	26.7	26.8	26.7	25.6	23.9	23.0

Table 2: Correlation coefficients between time series of seasonal total precipitation developed from the two gridded precipitation datasets (CRUTS and GPCC, see Table 1). Correlations are shown for three different seasons (MJJ, ASO and NDJFMA) and the annual total for four different time periods (1901-2009, 1921-2009, 1951-2009 and 1979-2009) for the four Caribbean regions (N, W, E and S). In the matrices below, the first four blocks contain correlations for the MJJ season above the diagonal and ASO below the diagonal. Bold values indicate correlations significant at the 95% level using a Student's t-test. The red values indicate correlations between the two datasets for the same region and season. The second set of four matrices contains correlations for the NDJFMA season above the diagonal and for the Annual totals below.

		MJJ 1901-2009							
		CRUTS N	CRUTS W	CRUTS E	CRUTS S	GPCC N	GPCC W	GPCC E	GPCC S
ASO 1901-2009	CRUTS N	--------	**0.33**	**0.43**	-0.05	**0.89**	**0.30**	**0.39**	-0.01
	CRUTS W	0.19	--------	**0.30**	0.00	**0.35**	**0.61**	0.16	-0.11
	CRUTS E	**0.39**	**0.22**	--------	-0.09	**0.49**	**0.21**	**0.68**	-0.18
	CRUTS S	**0.32**	**0.24**	0.15	--------	-0.10	-0.04	0.01	**0.77**
	GPCC N	**0.87**	**0.19**	**0.34**	**0.24**	--------	**0.27**	**0.34**	-0.05
	GPCC W	-0.04	**0.38**	0.01	0.11	0.01	--------	0.13	-0.11
	GPCC E	**0.31**	0.10	**0.53**	0.05	**0.35**	0.06	--------	-0.06
	GPCC S	**0.33**	**0.20**	0.17	**0.89**	**0.29**	0.03	0.07	--------

		MJJ 1921-2009							
		CRUTS N	CRUTS W	CRUTS E	CRUTS S	GPCC N	GPCC W	GPCC E	GPCC S
ASO 1921-2009	CRUTS N	--------	**0.42**	**0.48**	-0.07	**0.89**	**0.32**	**0.42**	-0.06
	CRUTS W	0.20	--------	**0.34**	0.02	**0.46**	**0.83**	**0.25**	-0.07
	CRUTS E	**0.38**	**0.22**	--------	-0.09	**0.52**	**0.29**	**0.83**	**-0.24**
	CRUTS S	**0.32**	**0.23**	0.15	--------	-0.10	-0.02	0.05	**0.78**
	GPCC N	**0.88**	**0.22**	**0.35**	**0.25**	--------	**0.28**	**0.40**	-0.10
	GPCC W	-0.09	**0.54**	0.07	0.02	-0.09	--------	**0.26**	-0.11
	GPCC E	**0.26**	0.12	**0.58**	0.10	**0.27**	0.15	--------	-0.06
	GPCC S	**0.35**	0.21	0.20	**0.90**	**0.34**	-0.08	0.20	--------

		MJJ 1951-2009							
		CRUTS N	CRUTS W	CRUTS E	CRUTS S	GPCC N	GPCC W	GPCC E	GPCC S
ASO 1951-2009	CRUTS N	--------	**0.35**	**0.49**	-0.12	**0.92**	**0.36**	**0.46**	-0.10
	CRUTS W	**0.33**	--------	**0.35**	-0.04	**0.43**	**0.92**	**0.36**	-0.12
	CRUTS E	**0.37**	**0.36**	--------	-0.12	**0.51**	**0.36**	**0.87**	**-0.30**
	CRUTS S	**0.37**	0.25	0.16	--------	-0.10	-0.07	-0.03	**0.80**
	GPCC N	**0.87**	**0.33**	**0.38**	**0.28**	--------	**0.38**	**0.46**	-0.10
	GPCC W	**0.30**	**0.90**	**0.28**	0.24	**0.28**	--------	**0.38**	-0.15
	GPCC E	**0.30**	0.17	**0.61**	0.08	**0.36**	0.11	--------	-0.15
	GPCC S	**0.43**	**0.26**	**0.29**	**0.93**	**0.39**	0.22	**0.27**	--------

		MJJ 1979-2009							
		CRUTS N	CRUTS W	CRUTS E	CRUTS S	GPCC N	GPCC W	GPCC E	GPCC S
ASO 1979-2009	CRUTS N	--------	0.15	0.15	-0.03	**0.84**	0.25	0.16	0.06
	CRUTS W	0.27	--------	0.27	0.18	**0.36**	**0.93**	0.27	0.05
	CRUTS E	**0.48**	0.34	--------	-0.09	0.34	0.19	**0.88**	-0.28
	CRUTS S	**0.39**	0.15	0.05	--------	0.07	0.10	-0.04	**0.81**
	GPCC N	**0.87**	0.27	**0.50**	**0.43**	--------	**0.36**	0.32	0.04
	GPCC W	0.19	**0.96**	0.21	0.07	0.21	--------	0.26	0.03
	GPCC E	**0.45**	0.30	**0.69**	0.21	**0.46**	0.19	--------	-0.08
	GPCC S	**0.46**	0.18	0.23	**0.91**	**0.54**	0.09	**0.40**	--------

		NDJFMA 1901-2009							
		CRUTS N	CRUTS W	CRUTS E	CRUTS S	GPCC N	GPCC W	GPCC E	GPCC S
ANN 1901-2009	CRUTS N	--------	**0.23**	**0.25**	**-0.25**	**0.78**	0.05	0.14	**-0.21**
	CRUTS W	**0.22**	--------	**0.21**	-0.14	**0.24**	**0.49**	0.06	-0.13
	CRUTS E	**0.45**	**0.27**	--------	0.06	0.15	0.02	**0.38**	0.03
	CRUTS S	0.12	0.00	0.16	--------	-0.10	0.06	0.17	**0.94**
	GPCC N	**0.85**	**0.23**	**0.38**	0.07	--------	**0.22**	0.18	-0.04
	GPCC W	0.02	**0.44**	-0.05	-0.07	0.11	--------	0.14	0.07
	GPCC E	**0.36**	0.06	**0.45**	**0.23**	**0.38**	0.04	--------	0.18
	GPCC S	0.17	-0.05	0.12	**0.89**	0.12	-0.11	**0.21**	--------

		NDJFMA 1921-2009							
		CRUTS N	CRUTS W	CRUTS E	CRUTS S	GPCC N	GPCC W	GPCC E	GPCC S
ANN 1921-2009	CRUTS N	--------	**0.24**	**0.25**	**-0.24**	**0.89**	0.12	0.17	-0.20
	CRUTS W	**0.28**	--------	**0.23**	-0.08	**0.29**	**0.70**	0.10	-0.03
	CRUTS E	**0.46**	**0.28**	--------	0.11	0.17	0.09	**0.45**	0.10
	CRUTS S	0.14	0.03	0.18	--------	**-0.21**	0.04	0.17	**0.95**
	GPCC N	**0.89**	**0.33**	**0.43**	0.07	--------	0.16	0.11	-0.16
	GPCC W	0.11	**0.69**	0.07	-0.10	0.17	--------	0.16	0.09
	GPCC E	**0.31**	0.15	**0.56**	0.19	0.20	0.13	--------	0.17
	GPCC S	0.20	0.02	0.14	**0.90**	0.15	-0.14	0.16	--------

		NDJFMA 1951-2009							
		CRUTS N	CRUTS W	CRUTS E	CRUTS S	GPCC N	GPCC W	GPCC E	GPCC S
ANN 1951-2009	CRUTS N	--------	0.17	0.21	-0.19	**0.89**	0.07	0.26	-0.15
	CRUTS W	**0.28**	--------	0.15	-0.15	0.18	**0.94**	-0.05	-0.11
	CRUTS E	**0.45**	**0.29**	--------	0.22	0.11	0.17	**0.66**	0.22
	CRUTS S	0.13	0.16	0.15	--------	-0.18	-0.16	0.03	**0.96**
	GPCC N	**0.92**	**0.31**	**0.41**	0.12	--------	0.07	0.09	-0.15
	GPCC W	**0.28**	**0.90**	**0.29**	0.09	**0.29**	--------	-0.10	-0.11
	GPCC E	**0.30**	0.10	**0.62**	0.00	0.26	0.13	--------	-0.02
	GPCC S	0.20	0.16	0.09	**0.90**	0.21	0.08	-0.03	--------

		NDJFMA 1979-2009							
		CRUTS N	CRUTS W	CRUTS E	CRUTS S	GPCC N	GPCC W	GPCC E	GPCC S
ANN 1979-2009	CRUTS N	--------	0.09	-0.03	-0.31	**0.83**	-0.06	0.03	-0.27
	CRUTS W	0.17	--------	0.06	0.09	0.13	**0.94**	-0.12	0.08
	CRUTS E	0.31	0.25	--------	0.23	-0.20	0.10	**0.71**	0.19
	CRUTS S	0.26	0.34	0.13	--------	-0.30	0.13	0.11	**0.93**
	GPCC N	**0.90**	0.21	0.33	0.32	--------	0.05	-0.30	-0.23
	GPCC W	0.09	**0.94**	0.18	**0.36**	0.15	--------	-0.21	0.17
	GPCC E	0.34	0.14	**0.72**	0.00	0.27	0.12	--------	0.01
	GPCC S	**0.38**	0.26	0.07	**0.84**	**0.47**	0.27	0.03	--------

Figure Captions

Figure 1: Station coverage for monthly precipitation totals (from CRU TS 3.21) across the region based on the 1951-2012 period. Filled circles have more than 50% completeness and unfilled circles less than 50% availability during the period. The shaded areas are those countries highlighted in Figure 3.

Figure 2: Station coverage for monthly temperature averages (from CRU TS 3.21) across the region based on the 1951-2012 period. Filled circles have more than 50% completeness and unfilled circles less than 50% availability during the period. The shaded areas are those countries highlighted in Figure 3.

Figure 3: The four geopolitical regions of the Caribbean used in this study (as defined by CARICOM, Caribbean Community and Common Market, a regional economic grouping).

Figure 4: Seasonal and annual precipitation anomaly (from 1961-90) time series for the North Caribbean region. Blue bars indicates seasons/years wetter than 1961-90 for the CRU TS 3.21 series with brown bars drier. The smooth lines are 10-year Gaussian smoothed series for CRU TS 3.21 and GPCCv5. Beneath the annual plot, the number of stations used per year is given.

Figure 5: Seasonal and annual precipitation anomaly (from 1961-90) time series for the East Caribbean region. Blue bars indicates seasons/years wetter than 1961-90 for the CRU TS 3.21 series with brown bars drier. The smooth lines are 10-year Gaussian smoothed series for CRU TS3.21 and GPCCv5. Beneath the annual plot, the number of stations used per year is given.

Figure 6: Seasonal and annual precipitation anomaly (from 1961-90) time series for the South Caribbean region. Blue bars indicates seasons/years wetter than 1961-90 for the CRU TS 3.21 series with brown bars drier. The smooth lines are 10-year Gaussian smoothed series for CRU TS3.21 and GPCCv5. Beneath the annual plot, the number of stations used per year is given.

Figure 7: Seasonal and annual precipitation anomaly (from 1961-90) time series for the West Caribbean region. Blue bars indicates seasons/years wetter than 1961-90 for the CRU TS 3.21 series with brown bars drier. The smooth lines are 10-year Gaussian smoothed series for CRU TS3.21 and GPCCv5. Beneath the annual plot, the number of stations used per year is given.

Figure 8: Annual temperature anomalies (°C from the 1961-90) period for the four Caribbean regions. Red bars indicates years warmer than 1961-90 for the CRU TS 3.21 series, with blue bars cooler. The smooth lines are 10-year Gaussian smoothed series. Beneath each plot, the number of stations used per year is given.

Figure 9: Precipitation trends (from CRU TS 3.21) across the Caribbean regions for the MJJ season for 1979-2012. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.

Figure 10: Precipitation trends (from CRU TS 3.21) across the Caribbean regions for the ASO season for 1979-2012. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.

Figure 11: Precipitation trends (from CRU TS 3.21) across the Caribbean regions for the NDJFMA season for 1979-2012. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.

Figure 12: Precipitation trends (from GPCCv5) across the Caribbean regions for the MJJ season for 1979-2009. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.

Figure 13: Precipitation trends (from GPCCv5) across the Caribbean regions for the ASO season for 1979-2009. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.

Figure 14: Precipitation trends (from GPCCv5) across the Caribbean regions for the NDJFMA season for 1979-2009. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.

Figure 15: Temperature trends (from CRU TS 3.21) across the Caribbean regions for the calendar year average 1979-2012. Units: °C/decade. Statistically significant trends at the 95% level are marked with a + sign.

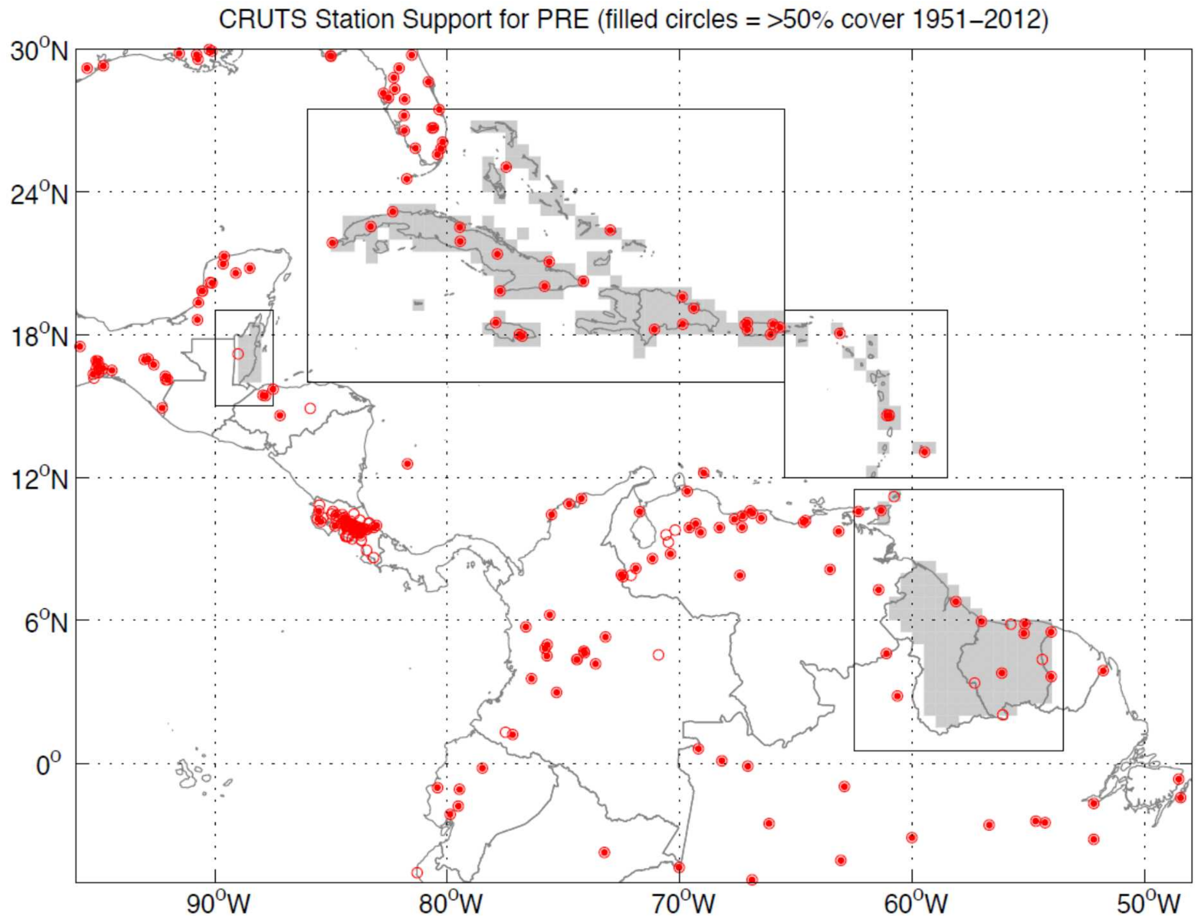


Figure 1: Station coverage for monthly precipitation totals (from CRU TS 3.21) across the region based on the 1951-2012 period. Filled circles have more than 50% completeness and unfilled circles less than 50% availability during the period. The shaded areas are those countries highlighted in Figure 3.

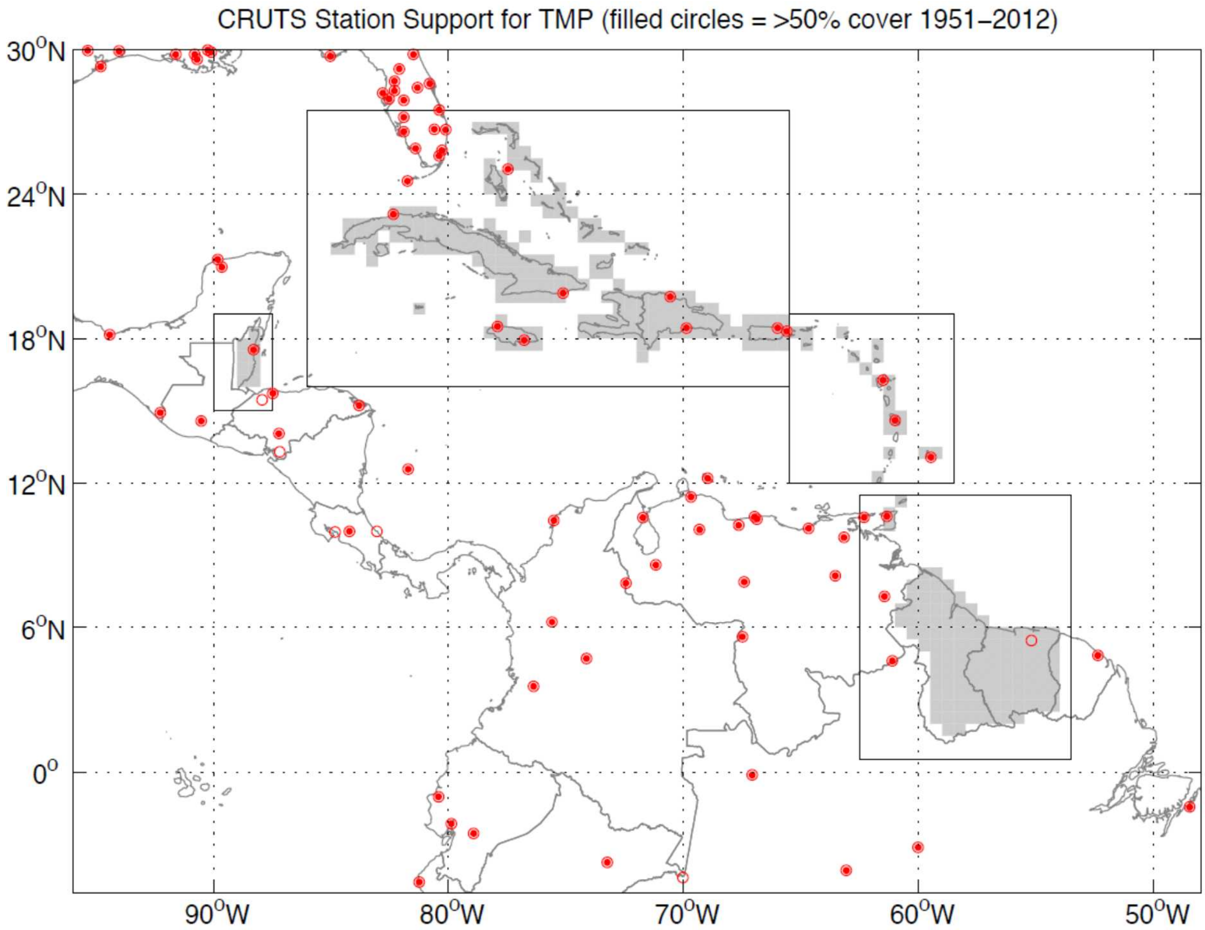
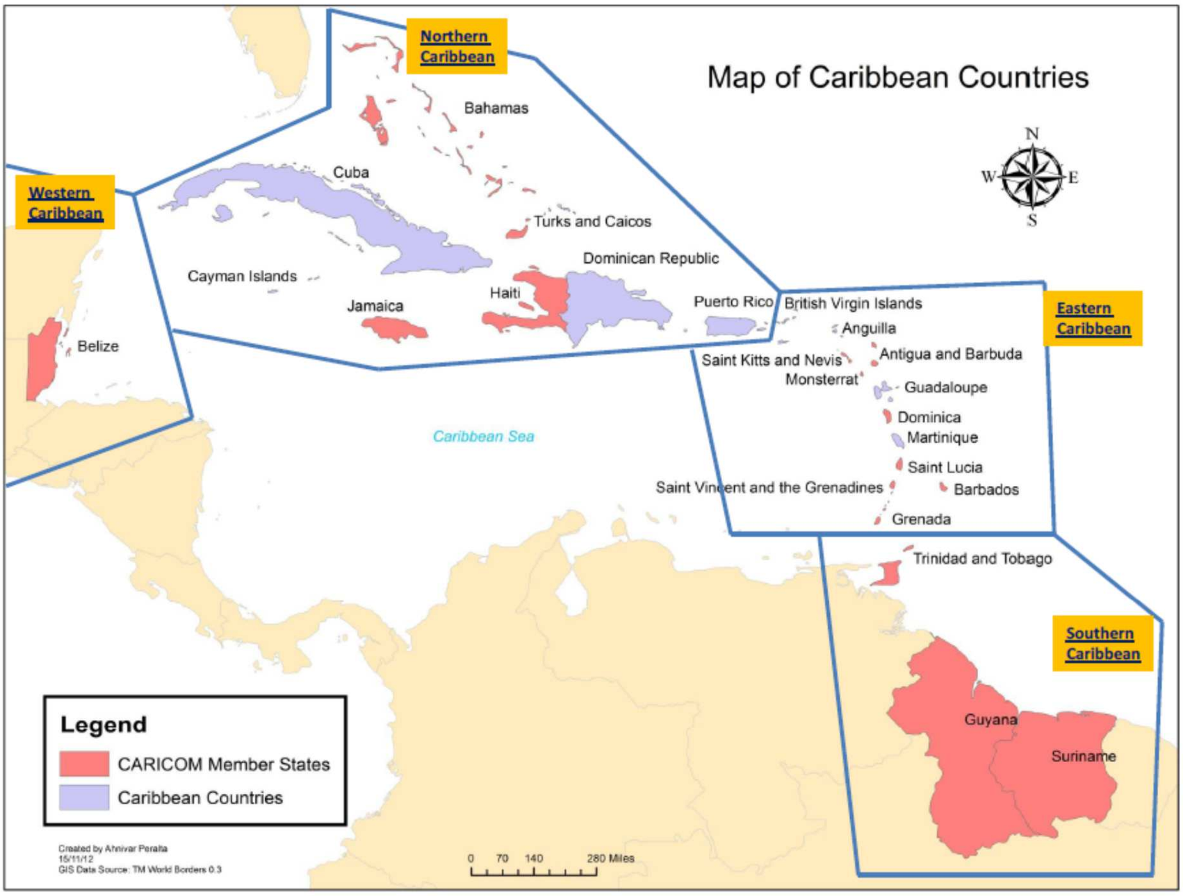


Figure 2: Station coverage for monthly temperature averages (from CRU TS 3.21) across the region based on the 1951-2012 period. Filled circles have more than 50% completeness and unfilled circles less than 50% availability during the period. The shaded areas are those countries highlighted in Figure 3.

Figure 3: The four geopolitical regions of the Caribbean used in this study (as defined by CARICOM, Caribbean Community and Common Market, a regional economic grouping).



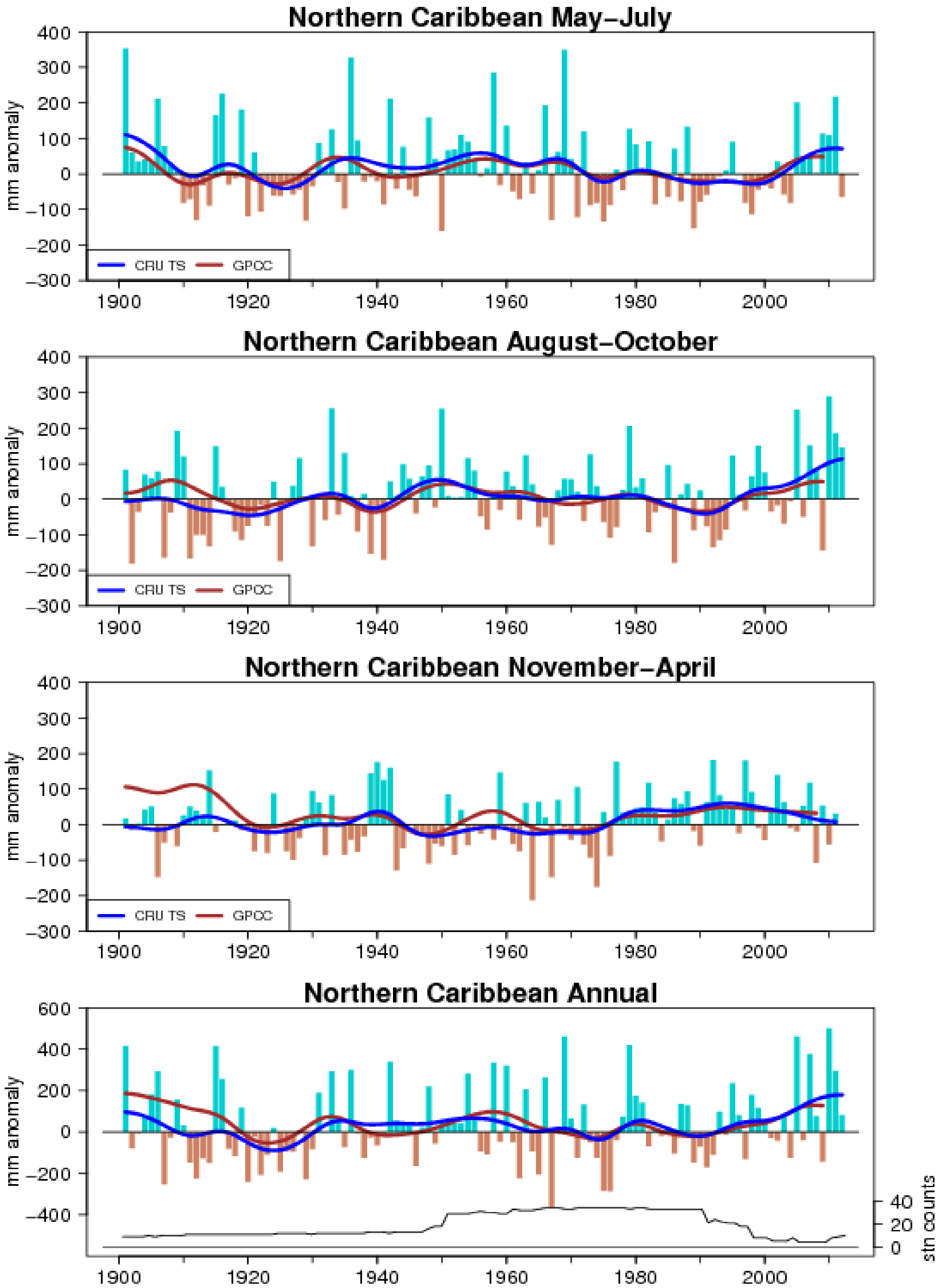


Figure 4: Seasonal and annual precipitation anomaly (from 1961-90) time series for the North Caribbean region. Blue bars indicates seasons/years wetter than 1961-90 for the CRU TS 3.21 series with brown bars drier. The smooth lines are 10-year Gaussian smoothed series for CRU TS 3.21 and GPCCv5. Beneath the annual plot, the number of stations used per year is given.

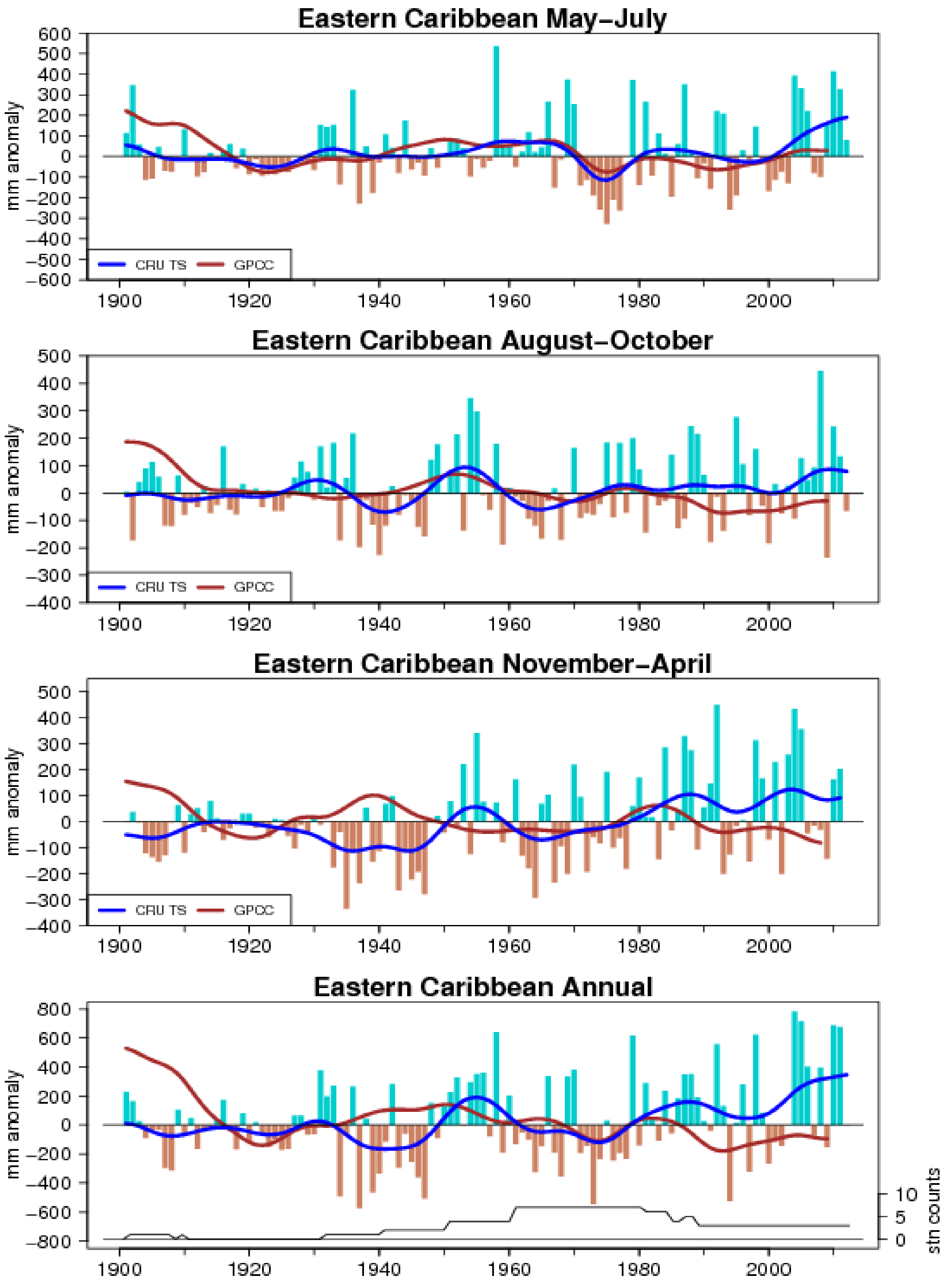


Figure 5: Seasonal and annual precipitation anomaly (from 1961-90) time series for the East Caribbean region. Blue bars indicates seasons/years wetter than 1961-90 for the CRU TS 3.21 series with brown bars drier. The smooth lines are 10-year Gaussian smoothed series for CRU TS3.21 and GPCCv5. Beneath the annual plot, the number of stations used per year is given.

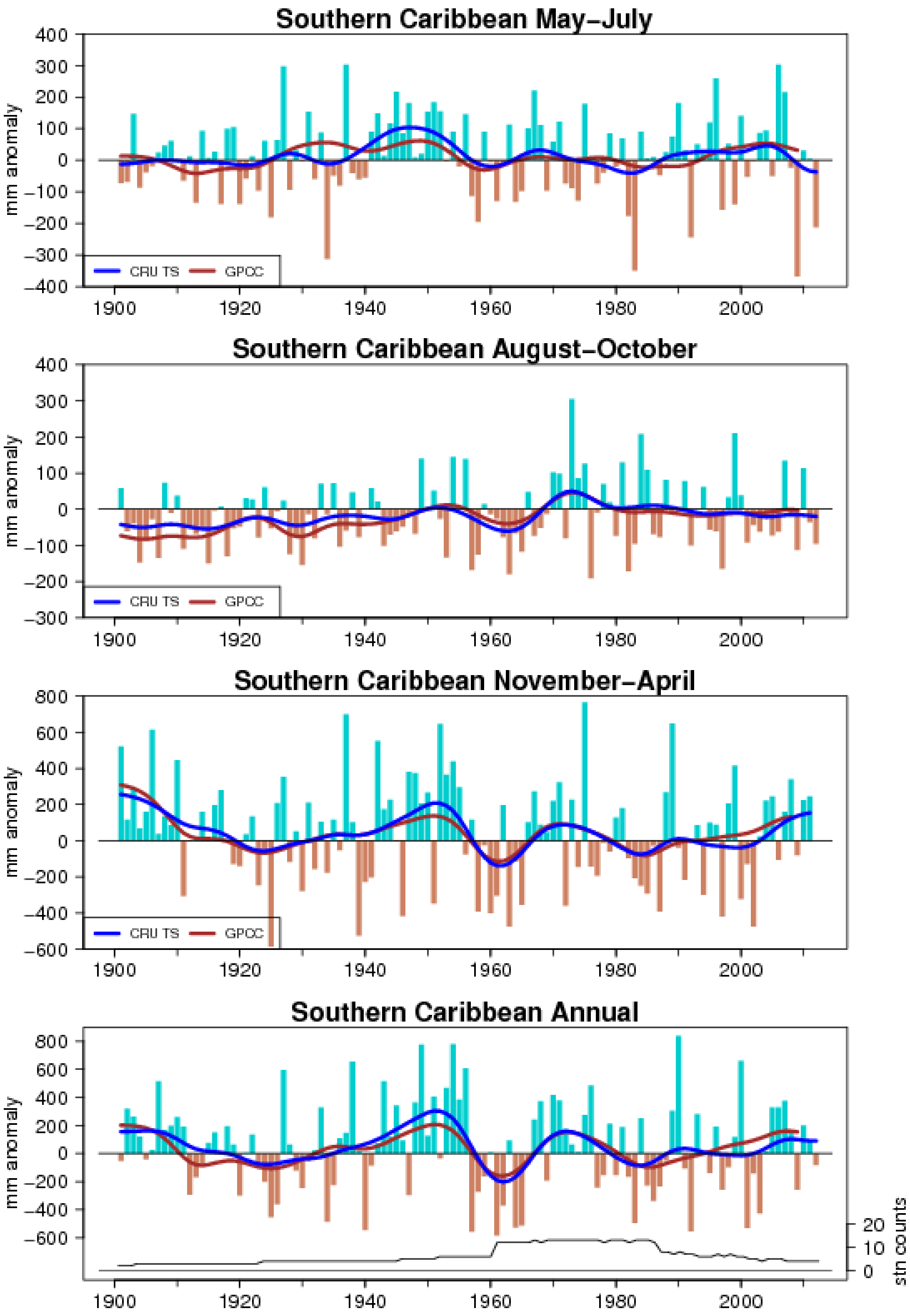


Figure 6: Seasonal and annual precipitation anomaly (from 1961-90) time series for the South Caribbean region. Blue bars indicates seasons/years wetter than 1961-90 for the CRU TS 3.21 series with brown bars drier. The smooth lines are 10-year Gaussian smoothed series for CRU TS3.21 and GPCCv5. Beneath the annual plot, the number of stations used per year is given.

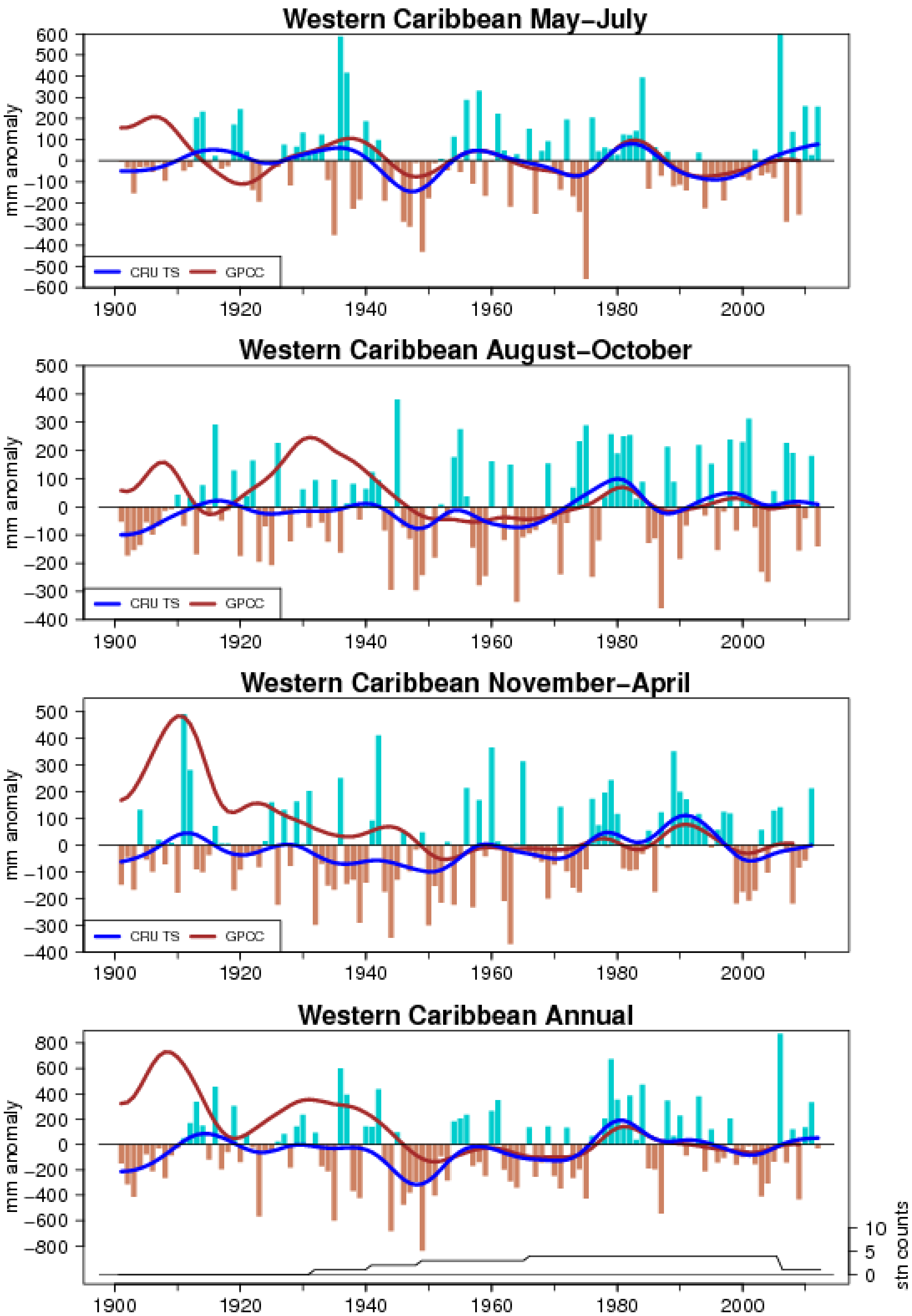


Figure 7: Seasonal and annual precipitation anomaly (from 1961-90) time series for the West Caribbean region. Blue bars indicates seasons/years wetter than 1961-90 for the CRU TS 3.21 series with brown bars drier. The smooth lines are 10-year Gaussian smoothed series for CRU TS3.21 and GPCCv5. Beneath the annual plot, the number of stations used per year is given.

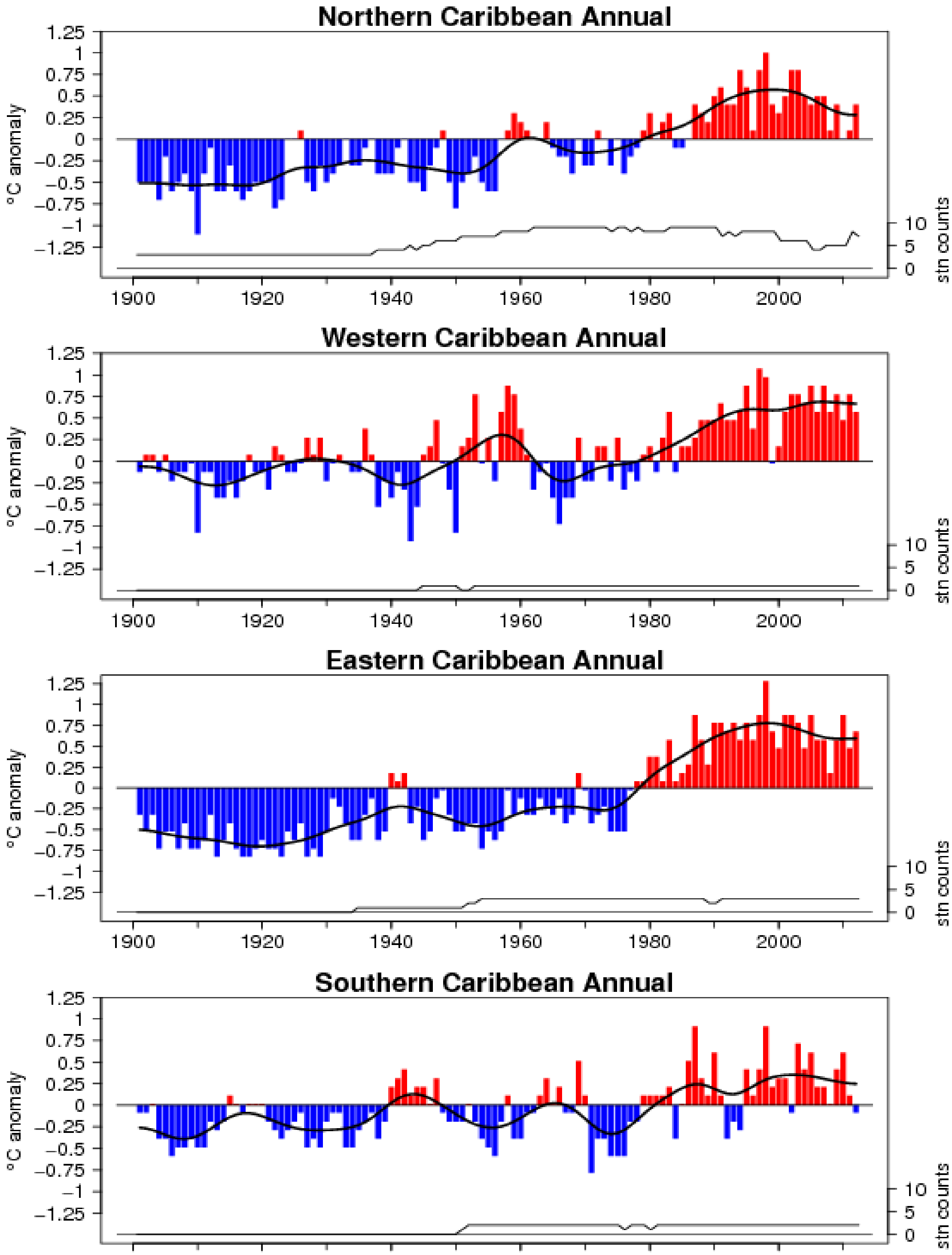


Figure 8: Annual temperature anomalies (°C from the 1961-90) period for the four Caribbean regions. Red bars indicates years warmer than 1961-90 for the CRU TS 3.21 series, with blue bars cooler. The smooth lines are 10-year Gaussian smoothed series. Beneath each plot, the number of stations used per year is given.

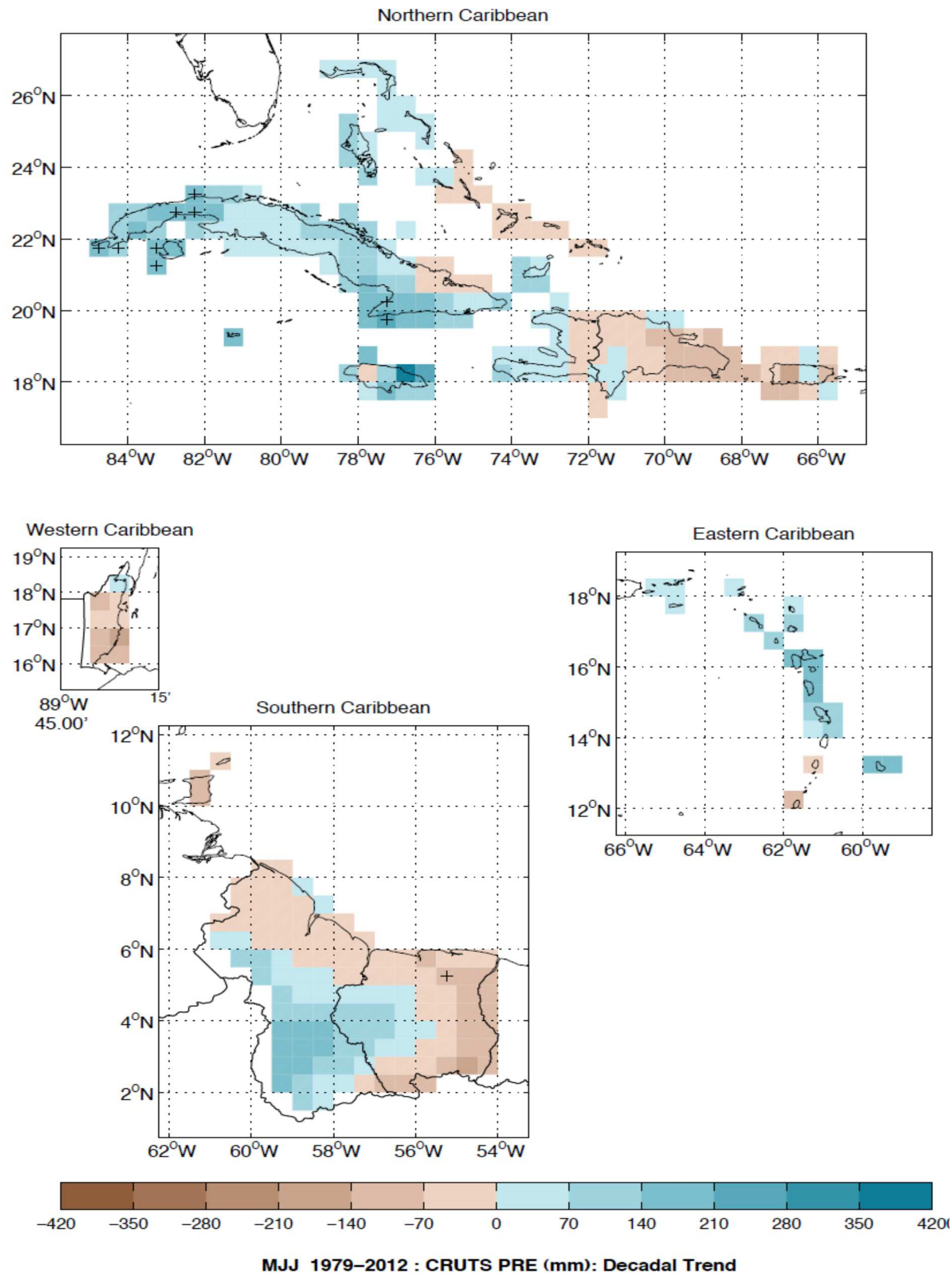


Figure 9: Precipitation trends (from CRU TS 3.21) across the Caribbean regions for the MJJ season for 1979-2012. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.

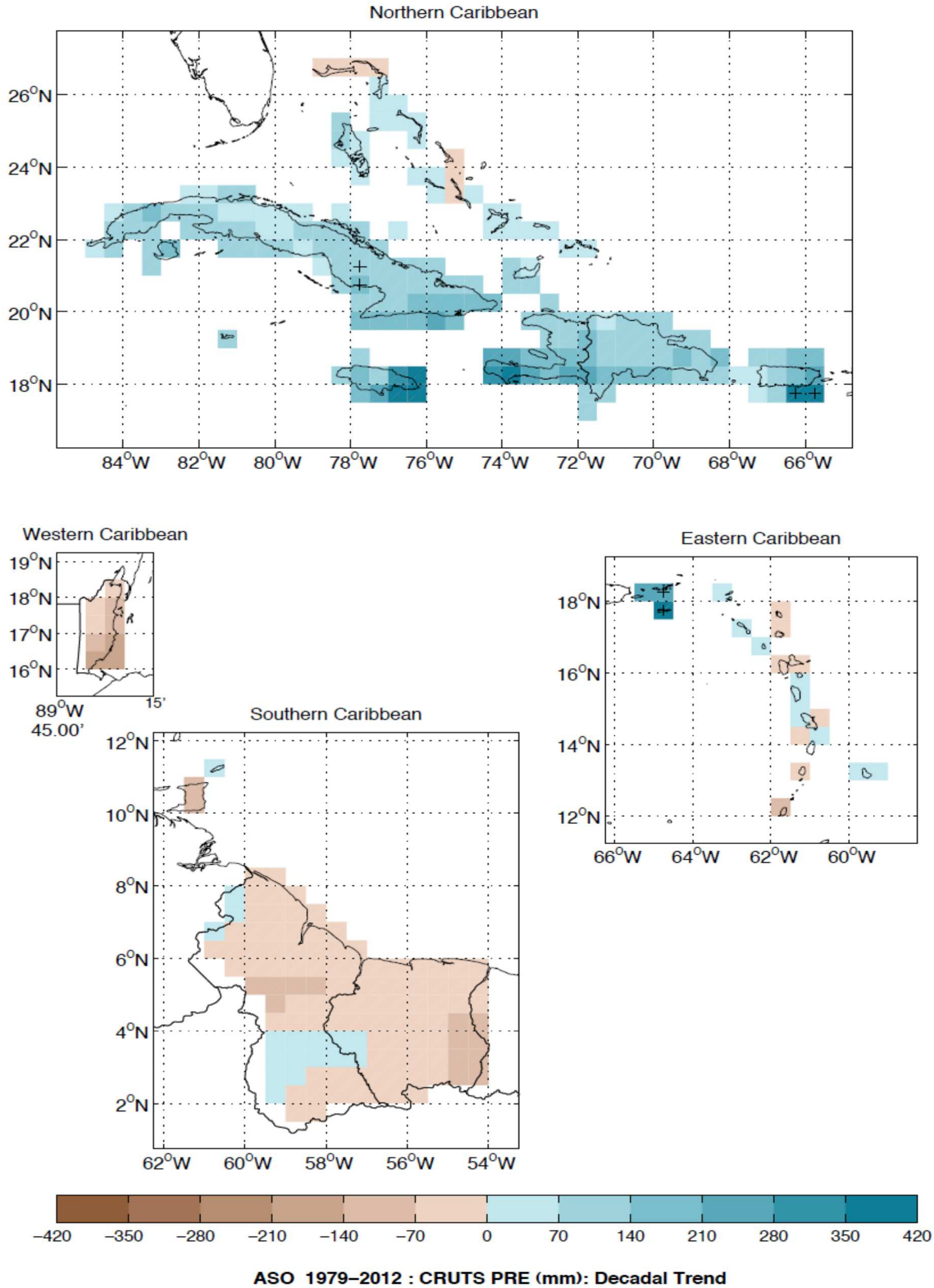


Figure 10: Precipitation trends (from CRU TS 3.21) across the Caribbean regions for the ASO season for 1979-2012. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.

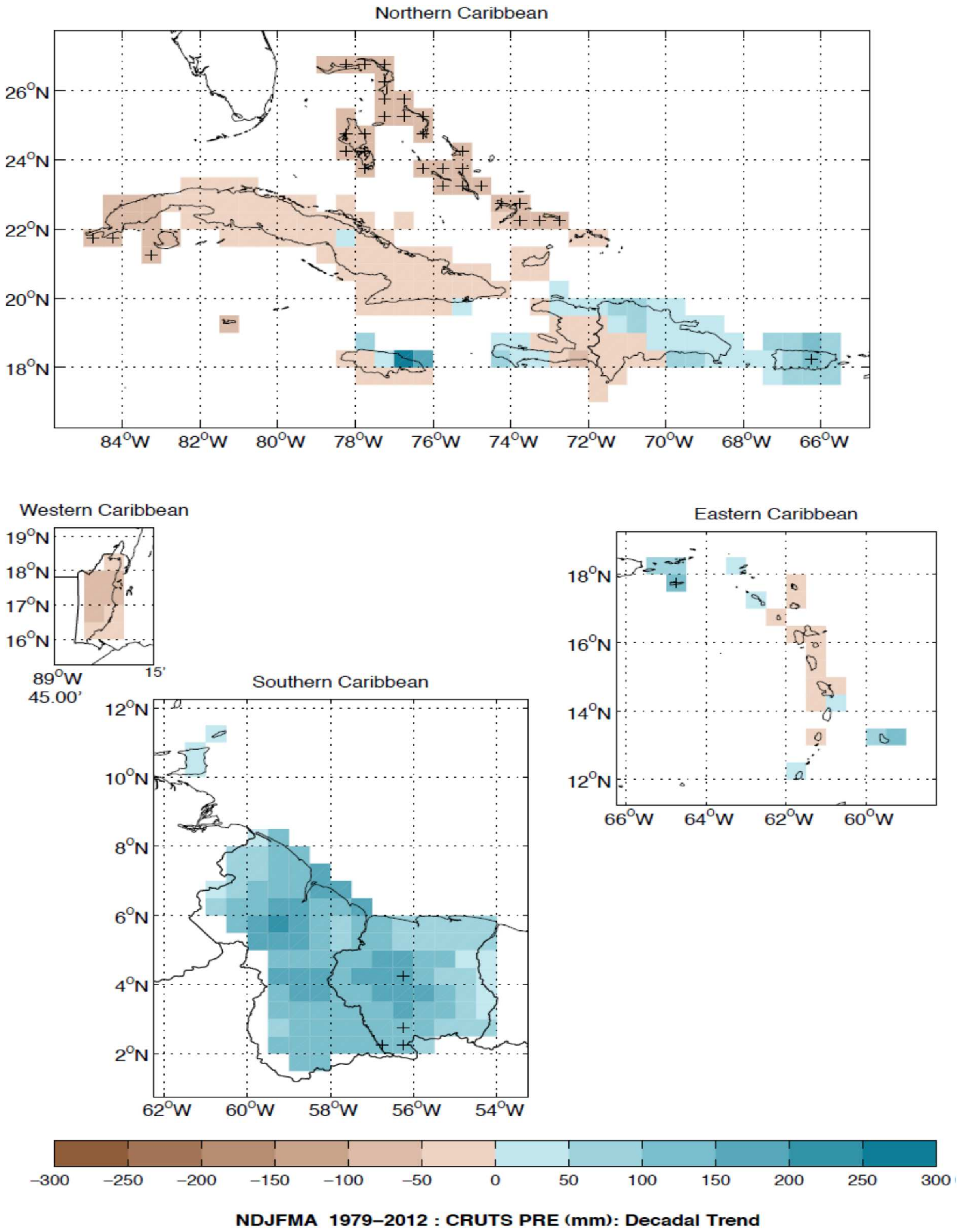


Figure 11: Precipitation trends (from CRU TS 3.21) across the Caribbean regions for the NDJFMA season for 1979-2012. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.

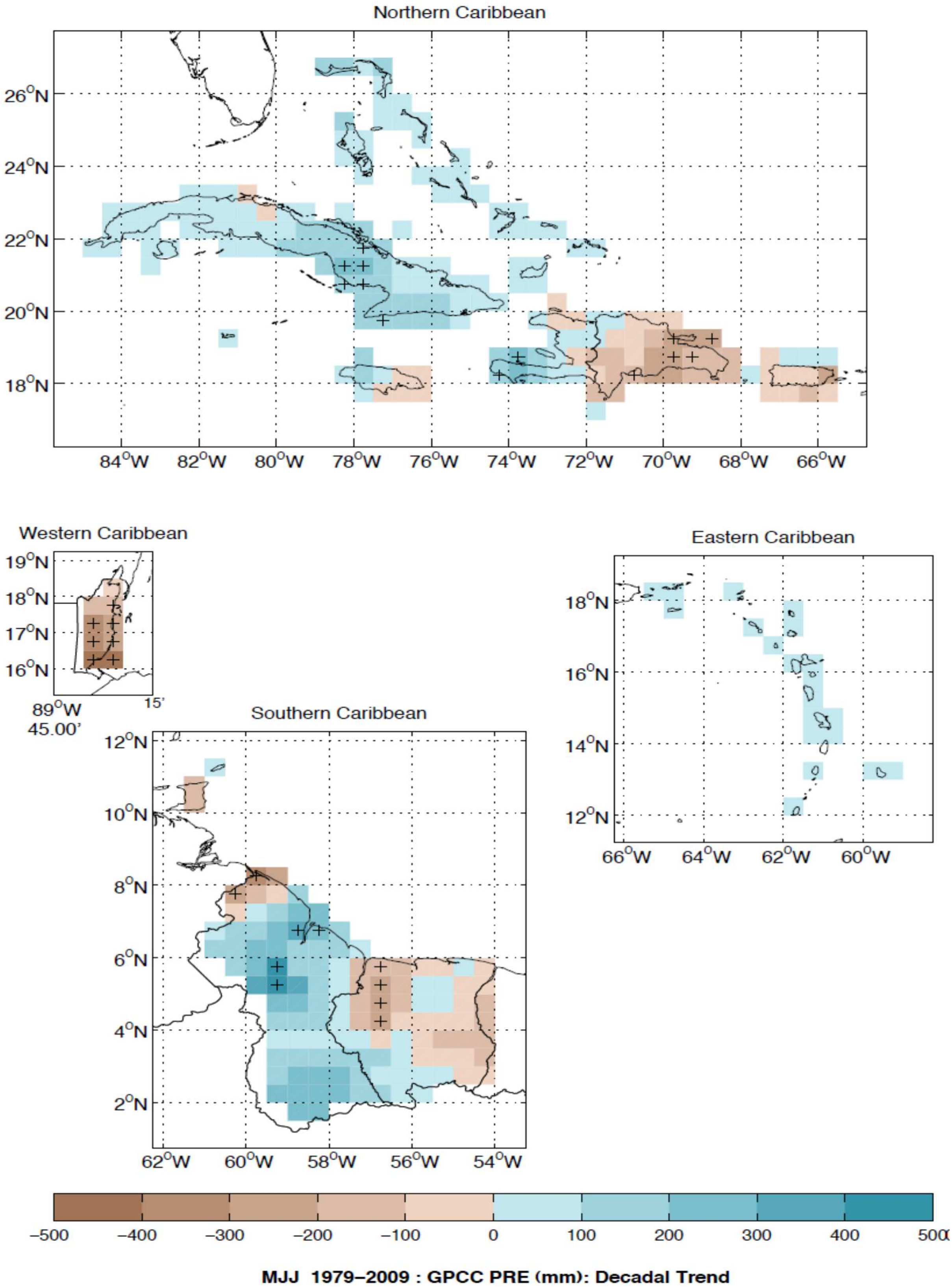


Figure 12: Precipitation trends (from GPCCv5) across the Caribbean regions for the MJJ season for 1979-2009. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.

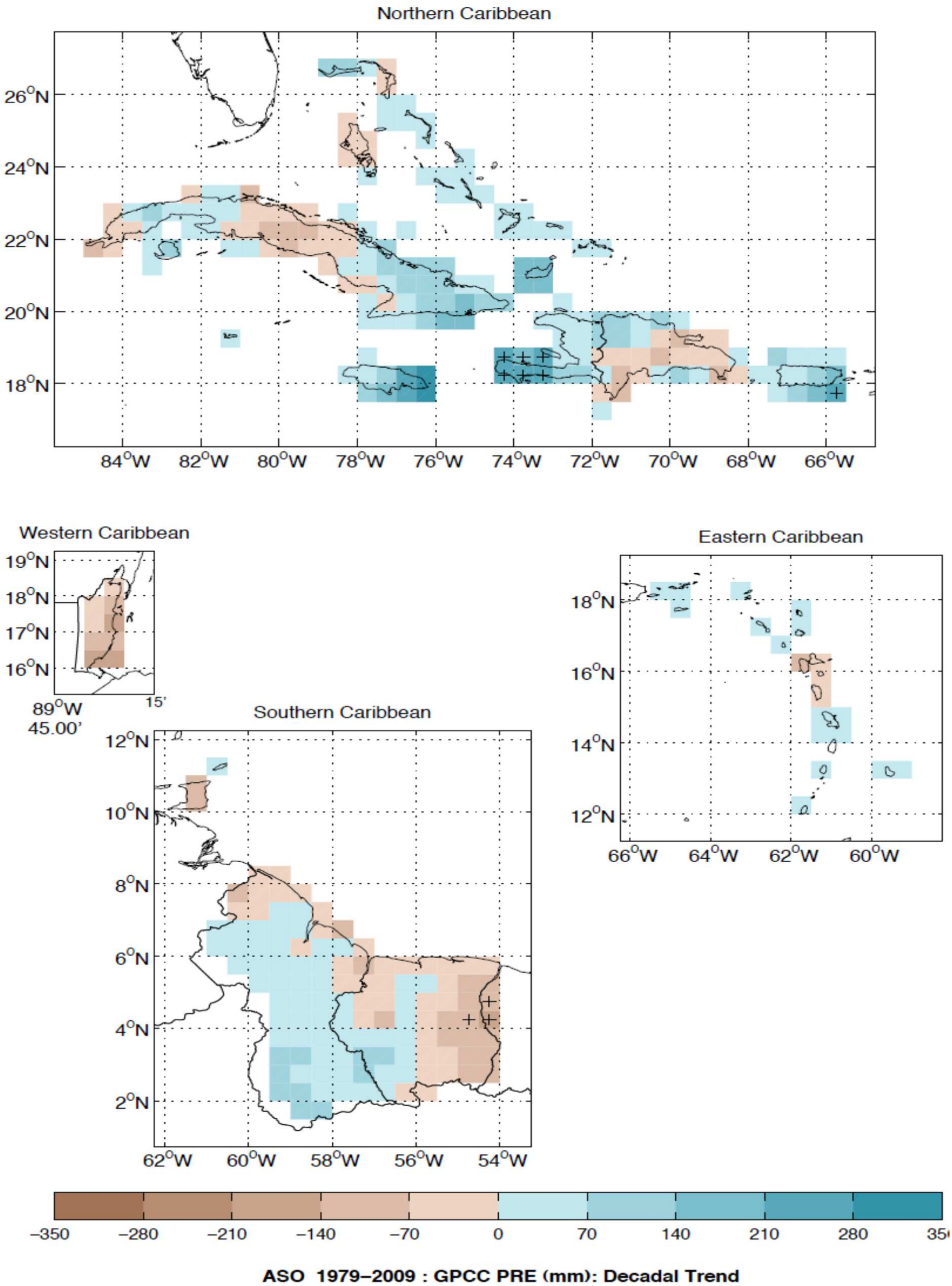
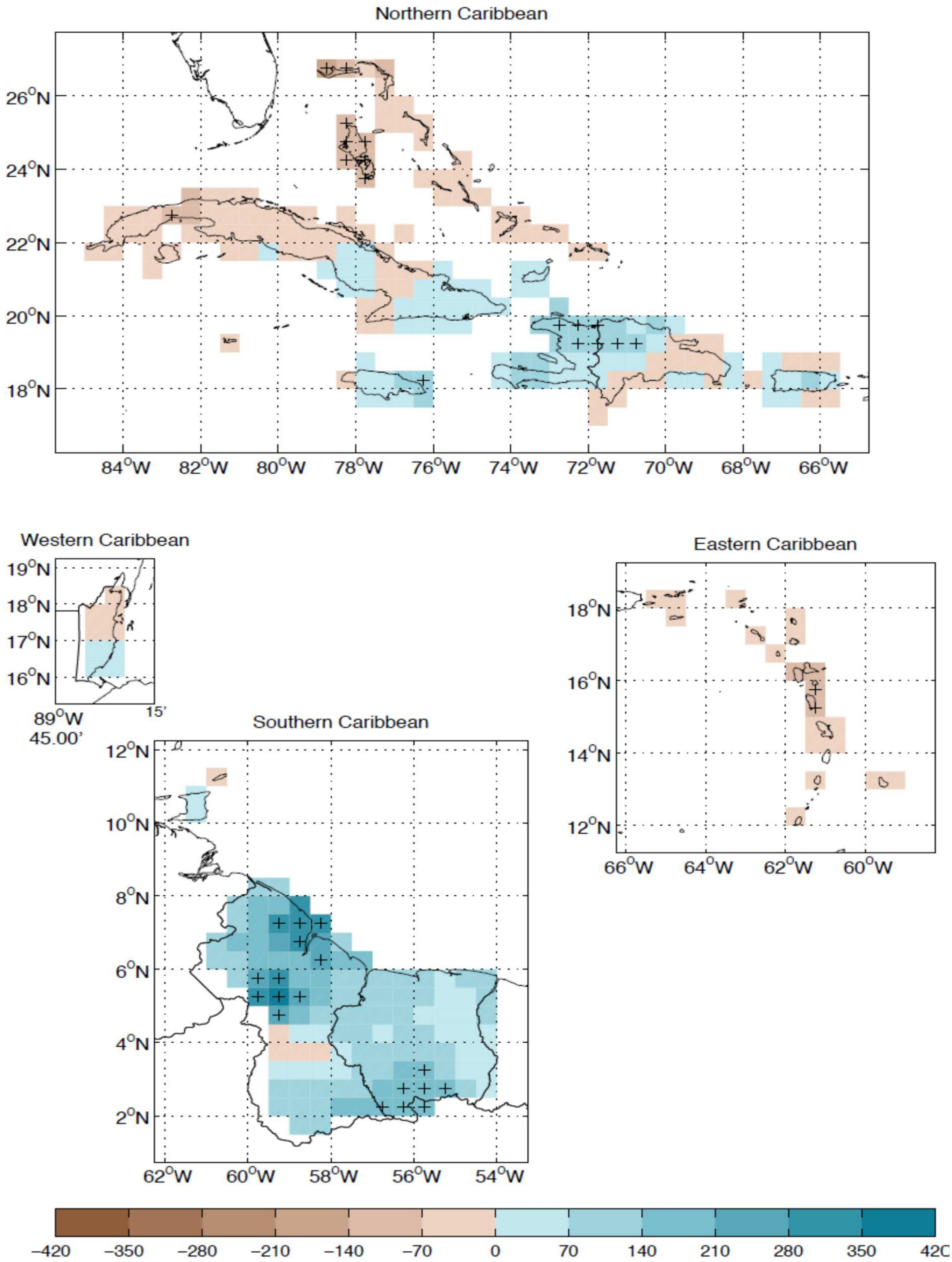


Figure 13: Precipitation trends (from GPCCv5) across the Caribbean regions for the ASO season for the 1979-2009. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.



NDJFMA 1979–2009 : GPCC PRE (mm): Decadal Trend

Figure 14: Precipitation trends (from GPCCv5) across the Caribbean regions for the NDJFMA season for the 1979-2009. Units: mm/decade. Statistically significant trends at the 95% level are marked with a + sign.

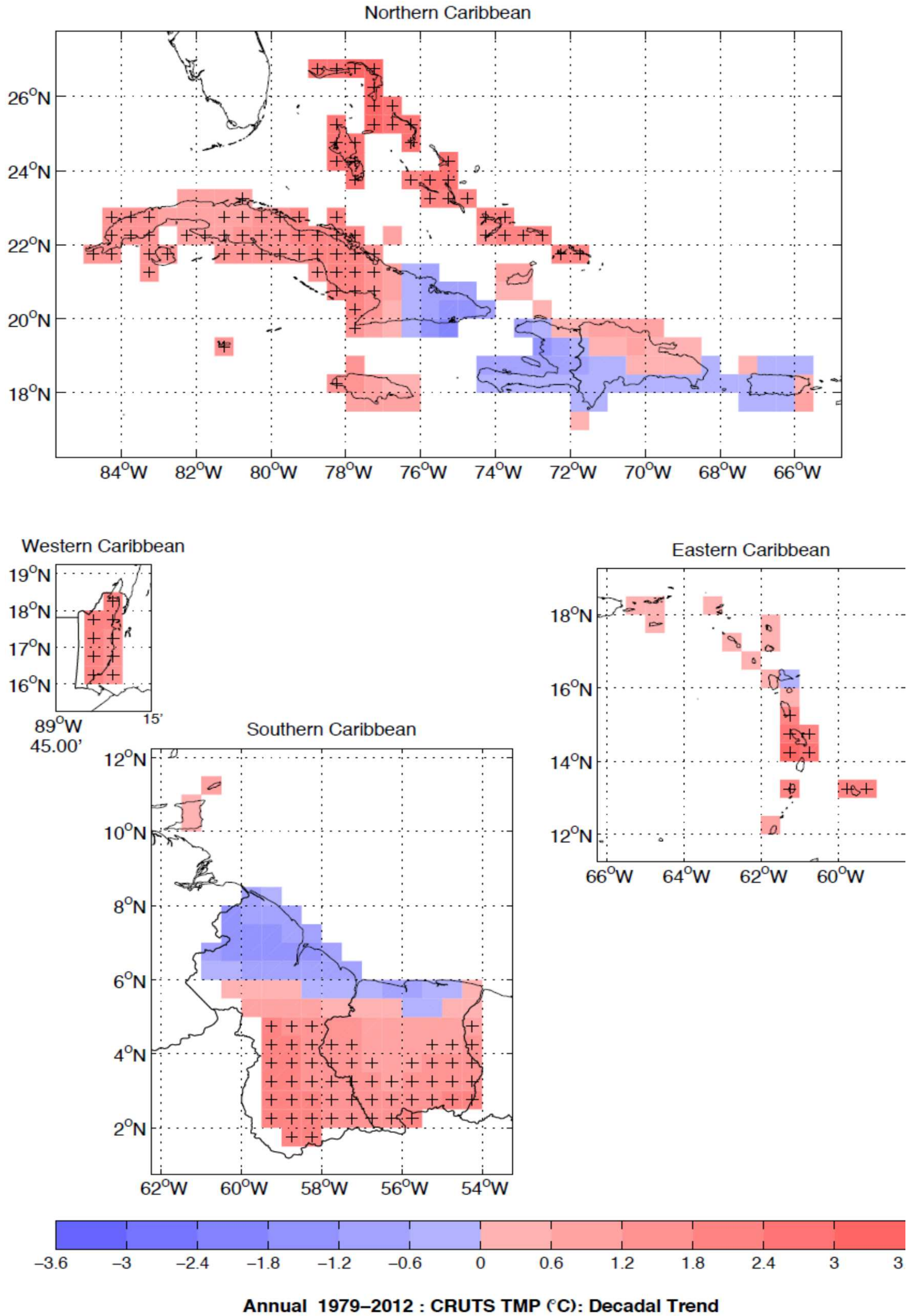


Figure 15: Temperature trends (from CRU TS3.21) across the Caribbean regions for the calendar year average for 1979-2012. Units: °C/decade. Statistically significant trends at the 95% level are marked with a + sign.