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Changes in extreme precipitation patterns over the greater Caribbean and teleconnection with large-scale sea surface temperature

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Abstract:

This study examines changes in extreme precipitation over the greater Caribbean and their correlation with large-scale sea surface temperature (SST) for the period 1985 to 2015. The data used for this study were derived from two satellite products: Climate Hazards Group InfraRed Precipitation (CHIRPS) and NOAA DOISST (Daily Optimum Interpolation Sea Surface Temperature version 2.1) with resolutions of 5 km and 25 km, respectively. Then, change in the characteristics of six(6) extreme precipitation indices defined by the WMO ETCCDI (World Meteorological Organization Expert Team on Climate Change Detection and Indices) is analyzed, and Spearman's correlation coefficient has been used and evaluated by t-test to investigate the influence of a few large-scale SST indices: (i) Caribbean Sea Surface Temperature (SST-CAR); (ii) Tropical South Atlantic (TSA); (iii) Southern Oscillation Index (SOI); (iv) Northern Oscillation Index (NAO). The results show that at the regional scale, +NAO contributes significantly to a decrease in heavy precipitation (R95p), daily precipitation intensity (SDII), and total precipitation (PRCPTOT), whereas +TSA is associated with a significant increase in daily precipitation intensity (SDII). At an island scale, in Puerto Rico and southern Cuba, the positive phase of +TSA, +SOI, and +SST-CAR is associated with an increase in daily precipitation intensity (SDII) and heavy precipitation (R95p). However, in Jamaica and northern Haiti, the positive phases of +SST-CAR and +TSA are also associated with increased indices (SDII, R95p). In addition, the SST warming of the Caribbean Sea surface temperature and the positive phase of the Southern Oscillation (+SOI) significantly increases with the number of rainy days (RR1) and the maximum duration of consecutive rainy days (CWD) over the Dominican Republic and in southern Haiti.

Keywords: Caribbean region; Greater Caribbean; Extreme precipitation; Climate variability; Sea surface temperature

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1 Introduction

Over the past three decades, the climatic hazards to which the Caribbean Basin has been exposed include recurrent cyclonic and hydrometeorological hazards, characterized by increasing intensities (Joseph, 2006). The economic cost of 250 storms and floods over a 40-year period (1970 to 2009) for 12 Caribbean countries amounted to US$19.7 billion in 2010, representing an annual average of 1% of gross domestic product (GDP) (Burgess et al., 2018). The most dreadful damage caused by these hydroclimatic events includes George in 1998, with 1,000 victims in the Dominican Republic and losses estimated at 14% of GDP, equivalent to approximately half the exports made that year (Naciones Unidades, Comision economica para America Latima y el Caribe, 1988); Matthew in Haiti (October 2016), with over 500 dead, 128 missing, 439 injured and 2.1 million people affected, including 895,000 children(De Giogi et al., 2021) . Also, Hurricane Dorian caused property damage estimated at 2.5 billion USD when it came to rest over the Bahamas as a Category 5 storm in September 2019, rendering nearly 3,000 homes uninhabitable and causing extensive damage to hospitals, schools, and fisheries (Panamerican Health Organisation, 2019). A severe drought episode affected the island of Caribbean from October 2019 to mid-2020, causing water shortages, bushfires, and agricultural losses. In Saint Vincent and the Grenadines, the 2020 drought was considered the worst of the 50 years (Nurse, 2020). The Inter-American Development Bank predicts that the Caribbean could face climate-related losses of over $22 billion per year by 2050 (Inter-American Development Bank, 2014).

In response to the climate extremes that are further weakening the island states of the Caribbean region, already in a situation of extreme socio-economic precariousness, several studies have been carried out in parallel to understand the associated physical processes and anticipate the evolution of these extreme climatic events. Research into the Caribbean climate goes back to the second half of the twentieth century and has focused mainly on rainfall patterns (Curtis et al., 2008), as well as on the overall description of rainy seasons (Griffiths et al., 1982).

A more detailed study of the climate of the Caribbean was performed in 2001 and 2002 using indices derived from daily data to detect climate change (Peterson et al., 2001; Frich et al., 2002). This approach, which uses indices defined by the World Meteorological Organization's group of experts to characterize precipitation and temperature extremes, has enabled several studies to examine the state of climate extremes over the Caribbean (Stephenson et al., 2014; McLean et al., 2015). The results of these previous assessments agree that the frequency and intensity of climate extremes over the Caribbean have increased over the last 30 years (Stephenson et al., 2014; Peterson et al., 2002a; Beharry et al., 2015; Dookie et al., 2019), and will continue to do so until the end of the century(Taylor et al., 2018; Vichot-Llano et al., 2021; Hall et al., 2013; Almazroui et al., 2021; McLean et al., 2015).

Climate teleconnections, the remote forcing of a region far from the source of disturbance, whether simultaneous or time-lagged (Mariami et al., 2018; Rodrigues et al., 2021), are generally derived from variations in sea surface temperature (SST) or atmospheric pressure at seasonal to interdecadal scales. Several of these have been shown to play a major role in modifying global weather patterns (Hurrell et al., 1995; Martens et al., 2018).

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Previous studies have also shown the effect of east-west gradients in SST anomalies in the tropical Pacific and Atlantic on precipitation in the Caribbean, with a tendency for a warm Atlantic and a cold Pacific to favor precipitation in the Caribbean (Taylor et al., 2002a; Gimeno et al., 2011). Studies in (Enfiel et al., 2001; IPCC, 2007) also found that the monthly AMO index is an SST signal in the North Atlantic that influences the decadal-scale variability in precipitation. In addition, (Peterson et al., 2022) analyzed the link between SST, air temperature, and precipitation extremes over the Caribbean using ground-based observations. They showed that the extreme precipitation index (SDII) averaged over the Caribbean has a strong correlation with SST over the Caribbean and the entire tropical North Atlantic Ocean. The work of (Stephenson et al., 2014) examined the influence of Atlantic Multidecadal Oscillation (AMO) on extreme precipitation from a ground-based observation network in the Caribbean. These results show that the AMO influences the variability of extreme temperature and precipitation events; however, further research is needed. In addition, the effects of teleconnections caused by large-scale SST on weather conditions are expected to become more extreme in the future due to climate change (Mariami et al., 2018).

In this context, the aim of this study was to examine the remote impact of the tropical Pacific Ocean, Atlantic Ocean, and Caribbean Sea on observed changes in the tropical islands of the Greater Antilles, particularly the links between extreme precipitation indices and large-scale sea surface indices. This paper is organized into five sections: Section 1 presents the study area and the associated climatology. Sections 2 and 3 describe the spatio-temporal variability of extreme precipitation indices at regional and local scales and the influence of SST indices on extreme precipitation. The last sections (4-5) present the discussion and conclusion.

2 Study area and Data

2.1 Study area

The Greater Antilles is a region between North and South America made up of four islands bordered by the Caribbean Sea to the south and the Atlantic Ocean to the east (Fig.1). These islands include Cuba, Hispaniola, Jamaica, and Puerto Rico. They have a monthly rainfall cycle characterized by two peaks: the first in May and the second between September and November. The climatology of monthly rainfall in the Greater Antilles is strongly influenced by the subtropical North Atlantic anticyclone (Davis et al., 1997), the easterly winds of the intertropical zone, and the trade winds (Cook et al., 2010). They were also influenced by the intertropical convergence zone (ITCZ) (Hastenrath et al., 2002), with maximum precipitation in May (fig.1b). Heavy autumn rainfall in the Greater Antilles (supl.fig.2d) is generally associated with North Atlantic tropical cyclones, 85% of which are of high intensity and originate from African easterlies (Agudelo et al., 2011; Thorncroft et al., 2001) under warm Atlantic basin conditions. The total annual precipitation in the Greater Antilles depends on land-sea interactions (breezes) and topography (fig.1a). The spatial distribution of the total annual precipitation in the Greater Antilles, particularly on the islands, is not homogeneous because of topography (Moron et al., 2015). Precipitation is relatively high (2,000-24,000< mm/year)

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at higher altitudes and in wind-exposed areas (fig.1b). In contrast, annual precipitation can reach 500 mm/year in leeward areas (Daly et al., 2003).

2.2 Satellite data

This study was conducted using two satellite datasets: NOAA DOISST Sea surface temperature data and CHIRPSv2 data. The CHIRPSv2 data (Climate Hazards Group Infrared Precipitation with Stations data version 2) are quasi-global daily precipitation data (50S-50N) with a resolution of 0.050, available over a period from 1981 to 2022(Funk et al., 2015). Based on the techniques used by NOAA for estimating precipitation in the thermal infrared (Love et al., 2004), the CHIRPS database was built from precipitation estimates based on cold cloud duration observations, and a fusion incorporating monthly CHPClim (Funk et al., 2015a) (Climate Hazards Group Precipitation Climatology (CHPClim) precipitation data, and in situ data from ground observation networks. TRMM 3B42v7 (Tropical Rainfall Measuring Mission Multi-Satellite Precipitation Analysis) satellite products were also used to calibrate and reduce the bias in the estimates. The results of global and regional validation studies showed that CHIRPS can be used to quantify the hydrological impacts of decreasing rainfall and increasing air temperatures in the Greater Horn of Africa (Funk et al., 2015). In addition, the performance of CHIRPS, evaluated over certain regions of the Americas, has demonstrated its ability to reproduce the mean climate as well as its capacity to estimate extreme precipitation events. For example, in Colombia, the best results were obtained on a daily and monthly scale over the Magdalena River Basin (the largest in Colombia) (Baez-Villanueva et al., 2018). CHIRPS data are suitable for our study, as their performance over the Caribbean, particularly the Greater Antilles, has shown their ability to estimate heavy precipitation (Bathelemy et al., 2022).

NOAA DOISST (Daily Optimum Interpolation Sea Surface Temperature version 2.1) data are daily sea surface temperature data derived from a combination of in situ sea surface temperature (SST) data obtained from ships and buoys and sea surface temperatures obtained from the Advanced Very High Resolution Radiometer (AVHRR)(Huang et al., 2021). This satellite product is the result of a global file of 0.250-degree grid points, available over the period 1981-2020.

3. Methodology

To provide countries with information on extreme weather events, a group of World Meteorological Organization experts (ETCCDI: Expert Team on Climate Change Detection and Indices) defined 27 indices to characterize extreme precipitation and temperature events in terms of their frequency, amplitude, and duration (Peterson et al., 2001). Although the proposed method includes numerous indices based on percentiles, with thresholds set to assess extremes

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that generally occur a few times a year and not necessarily high-impact events, it has paved the way for numerous research projects in the Caribbean (Stephenson et al., 2014; McLean et al., 2015). Six (6) extreme precipitation indices (Table 1) were calculated: total annual precipitation (PRCPTOT), number of rainy days (RR1), intensity of rain events (SDII), and heavy precipitation (R95p), calculated in relation to a threshold corresponding to the 95th percentile of the daily precipitation distribution, maximum number of consecutive wet days (CWD), and maximum number of consecutive dry days (CDD).

The spatiotemporal evolution of extreme precipitation in the Greater Antilles was investigated by analyzing the interannual variability of extreme precipitation index anomalies over a long period (1985-2015) and the change in percentage variations in extreme precipitation indices at decadal timescales. To characterize the percentage variations, we chose the (Pij) index, which is already used in the study (An et al., 2023), whose equation is presented hereafter.

$$P_{ij} = \left(\frac{P_{i(j+1)}}{P_{ij}} - 1 \right) \times 100 \qquad (1)$$

where Pij is the average extreme precipitation index for the j-th decade at the i-th location, and Pi(j+1) is the average extreme precipitation index for the (j+1)-th decade at the i-th location.

Then, as the variability of precipitation in the region is known to be linked to SST in the tropical Pacific and Atlantic(Gimeno et al., 2011; Enfiel et al., 2001), we selected four large-scale SST indices, namely the Southern Oscillation Index (SOI), the North Atlantic Oscillation (NAO)(Jones et al., 1997), the Tropical South Atlantic Anomaly Index (TSA), and the SST over the Caribbean Sea (SST-CAR), and investigated the teleconnection between these indices and the precipitation extremes in the region. Detailed descriptions and estimates of these SST indices are available in (https://psl.noaa.gov/data/climateindices/list/#Nina34).

The teleconnection between SST and extreme precipitation indices was assessed using Spearman's correlation coefficient analysis. Such an analysis with Spearman correlation has already been carried out in the study of (Khadgarai et al., 2021), as well as in other studies on spatial correlation (Chen et al., 2015; Sunilkumar et al., 2016) . This coefficient was interpreted over a closed interval between -1 and 1. A value of zero (0) indicates that there is no relationship between the two variables; a negative value (negative correlation) indicates that when one variable increases, the other decreases, while a positive value (positive correlation) indicates that the two variables vary in the same direction. Spearman's correlation coefficient is calculated using the following equation:

$$r\_spearman = \frac{\sum_{i=1}^{n} (R_i - \bar{R})\,(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n} (R_i - \bar{R})^2 \sum_{j=1}^{n} (S_i - \bar{S})}} \qquad (2)$$

where r_spearman is the correlation coefficient, Ri=rang (Xi), Si=rang (Yi) are respectively the data ranks of Variables X and Y (X: Extreme precipitation index, Y: Large-scale SST index).

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To test the significance of the relationship, that is, whether the two variables are really correlated or not, we use the t-test for a threshold of 0.05 or less. This involves testing the two hypotheses (H0 and H1) based on the value of t to deduce the probability of observing a result that deviates as much as expected from the correlation. The formula for calculating the value of t using Spearman's correlation is as follows:

$$t_{n-2} = \frac{r_{spearman}}{\sqrt{1-r_{spearman}^2}}\sqrt{n-2} \quad (3)$$

4 Results

4.1 Changes in precipitation extreme indices

The observed changes in total annual precipitation (PRCPTOP), number of rainy days (RR1), rainfall intensity (SDII), contribution of heavy rainfall (R95p), and maximum duration of consecutive rainy days (CWD) and dry days (CDD) in the Greater Antilles over the three decades (1985-1994, 1995-2004, 2005-2015) are shown in fig. 2. The first decade of 1985-1994 was generally marked by a decline in total annual precipitation (fig.2a), associated with a decrease in the number of rainy days (fig. 2b), a decrease in the average rainfall intensity (fig. 2c), a decrease in the contribution of heavy rainfall (fig. 2d), and in the length of wet and dry spells (fig. 2e, 2f). The second decade 1995-2004, was mainly characterized by an increase in rainfall associated with an increase in rainfall intensity, the contribution of heavy rainfall, and the length of dry spells. The last decade 2005-2015, was characterized by a wet period (until 2012) followed by a dry period. Except for 2008-2009, the wet period was generally associated with positive anomalies of all indices, whereas the last dry period exhibited negative anomalies in all indices except during rainy days, which showed a weak change.

Fig. 3 shows the annual change in % between two consecutive decades of precipitation indices over the Greater Antilles (1985-2015). As shown in fig. 3a, there was an increase in total annual precipitation (PRCPTOT) in southeastern Cuba. This was associated with an increase in the number of rainy days (RR1) (fig.3c) and the average intensity of precipitation per rainy day (SDII) (fig.3c). These results were also observed in Jamaica (fig.3a, 3c). In addition, a decrease in total annual precipitation (PRCPTOT) was observed on the island of Hispaniola (Haiti and the Dominican Republic) (fig.3a). This was associated with a decrease in the average rainfall intensity per wet day (SDII) (fig.3c). This decrease in the SDII was also recorded in Puerto Rico (fig.3c). For heavy precipitation (R95p), as shown in fig.3d, an increase was observed in the southeastern part of Cuba, whereas the whole island (Cuba) was affected by a decrease in wet sequences (CWD) (fig.3e) and dry sequences (CDD) (fig.3f). A decrease in heavy precipitation (R95p) was observed in the central and western regions of Haiti (fig.3d). This was accompanied by an increase in wet sequences (CWD) over Haiti (fig.3e). The Dominican Republic was also affected by this increase in wet sequences (CWD) (fig.3e).

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Variations in extreme precipitation indices under the influence of variables such as NAO, SOI, TSA, and SST-CAR were analyzed over the Greater Antilles. The influences of large-scale variables were classified as positive, negative, positive, significant, negative, or significant, as shown in figure 4. The results obtained by taking the intersections of the tables presented show the values of the correlation coefficient (with its significance *) between the extreme precipitation indices (PRCPTOT, RR1, SDII, R95p, CWD, and CDD) and the influencing variables (NAO, SOI, TSA, and SST-CAR). The tables in fig. 4 show that NAO has a negative effect on all extremes, while the other SST are positive, except for the number of rainy days (RR1) and the number of consecutive rainy days (CWD). However, the positive phase of the +TSA index had a positive and significant effect on the average rainfall intensity per wet day (SDII), for which a correlation coefficient of 0.37 was obtained. Similarly, with the ONA index, a negative and significant effect ($P<0.05$) was observed on total annual precipitation (PRCPTOT), average precipitation intensity (SDII), and heavy precipitation (R95p), for which correlation coefficients of 0.49, 0.40, and 0.47, respectively, were obtained.

At a local scale, the results show that teleconnections have had positive and significant effects on extreme precipitation indices over the last 30 years in the countries of the Caribbean region, particularly in the Greater Antilles. The spatial extent of significance is indicated by the symbols (*). Thus, a double symbol (**) indicates that the effect extends over a wide area, whereas the effect is limited to that bearing a single symbol (*). The figures ($P \leq 0.05$; fig. 5, 6, 7, 8) show the regions or countries over which positive and significant effects were observed for the Greater Antilles.

Fig. 5 and suppl. Table 1 shows the effect of the TSA index on extreme precipitation indices (PRCPTOT, RR1, SDII, R95p, CWD, and CDD) in the Greater Antilles. The results show that South Atlantic tropical warming, corresponding to the positive phase of the +TSA index, has a positive and significant effect (**) on the total annual precipitation (PRCPTOT) and heavy precipitation (R95p) in Puerto Rico (fig.5a, 5b; suppl. table1d). In Jamaica, it was also associated with an increase in total annual precipitation (PRPCPTOT) and heavy precipitation (R95p) in Puerto Rico (fig.5a, 5b; suppl. table1d). In Haiti, more specifically in the northern part, the increase in the average daily rainfall intensity (SDII) was also associated with +TSA warming (fig.5e; suppl. table1d). In northwest Cuba, this positive phase of +TSA also had a positive and significant effect (**) on mean rainfall intensity per day (SDII) (fig.5e; suppl. table1d). Conversely, in southeastern Cuba, a positive effect was observed for heavy rainfall (R95p) (fig.5b; suppl. table1d).

Fig. 6 and suppl. Table 2 shows the effects of warming of the Caribbean Sea surface temperature (SST-Car anomaly, averaged over 14-16N, 65–85 °W) on extreme precipitation in the Greater Antilles. In southern Haiti, an increase in total annual precipitation (PRCPTOT) and the number of rainy days (RR1) was observed as the SST-Car warmed (fig.5a, 5c; suppl. table1a). This increase was also observed for heavy rainfall (R95p) (fig.6b; Suppl. table1a). In eastern Haiti, particularly in Santo Domingo, the positive phase of SST-Car is associated with an increase in the duration of wet sequences (CWD) and the number of rainy days (RR1) (fig.6e, 6c; suppl. table1a). In southeastern Cuba, warming of SST-Car is associated with an increase in total annual precipitation (PRCPTOT) and heavy

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precipitation (R95p) (fig.6a, 6b; suppl. table1a). An increase in heavy precipitation (R95p) during the positive phase of + SST-Car was also observed in Puerto Rico (fig.6c; Suppl. table1a).

Fig. 7 and suppl. table1 show the results of the effect of SOI on extreme precipitation indices (PRCPTOT, RR1, SDII, R95p, CWD, and CDD) in carabid beetles, particularly on the islands forming the Greater Antilles. In Puerto Rico, as shown (fig.7a, 7b; suppl. table1c), the positive phase of the +SOI index was associated with an increase in total annual precipitation (PRCPTOT) and heavy precipitation (R95p). In Haiti, specifically in the south, this positive phase of the +SOI index was associated with an increase in the number of rainy days (RR1), including the duration of wet sequences (CWD) (fig.7c, 7d; suppl. table1c). In Santo Domingo, this is associated with an increase in the duration of wet sequences (CWD) (fig.7d; suppl. table1c). In southeastern Cuba, this is associated with an increase in the average intensity of precipitation per rainy day (SDII) and heavy precipitation (R95p) (fig.7e, 7b; suppl. table1c).

Fig. 8 and suppl. table1 show the results of the effect of the NAO index on extreme precipitation indices (PRCPTOT, RR1, SDII, R95p, CWD, and CDD) in the Greater Antilles. The condensed results for different phases of the NAO index are presented in Supplementary Table 1b. In contrast to the results for the other ESS, the positive phase of the +NAO index was only associated with an increase in the number of rainy days (RR1) over Cuba. This increase was greater for coasts facing the Caribbean Sea (fig.8c; Suppl. table1b).

5. Discussion

The results concerning the effect of the Atlantic Ocean, tropical Pacific, and Caribbean Sea on extreme precipitation indices show that extremes are influenced differently by the oceans and the Caribbean Sea. Moreover, at a local or regional scale, the correlation coefficients measuring trends in this influence are not statistically significant. To clarify these results, we separately discuss the effects of indices (NAO and SOI) and sea surface temperature anomalies (SST-Car, TSA) on extreme precipitation indices.

5.1 Effect of sea surface pressure anomalies (NAO, SOI)

In this study, the effects of the Atlantic Ocean on the Greater Antilles are measured using two indices (NAO and TSA) defined over two ocean areas in two hemispheres. For the Northern Hemisphere, it has been shown that the phases (positive and negative) of the NAO index affect circulation on a Northern Hemisphere scale (Thompson et al., 2000). NAO index results show that the effect produced by the negative phase, corresponding to a weakening of the subtropical anticyclone (Wallace et al., 1981; North Atlantic Oscillation, 2023) and leading to very wet conditions over the Caribbean, particularly the Greater Antilles (Mo et al., 2005; Mestas-Nuñez et al., 2007), is associated with a negative effect on all regional extremes. In other words, the NAO index evolves with extremes in the opposite direction, that is, the negative (positive) phase of the NAO is linked to the positive (negative) phase of the precipitation

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indices. This indicates that the extreme precipitation indices are modulated by the positive and negative phases of the North Atlantic Oscillation (NAO).

At a local scale, the effect is observed on all extremes, except for the number of rainy days (RR1). Despite less favorable conditions for precipitation, because the +NAO index is in a positive phase, an increase is recorded on the southern coasts of Cuba and Haiti, whose coastline is the Caribbean Sea.

In the case of the SOI, studies have shown that the phenomena induced by phase changes (El Niño, La Niña) have a considerable impact on temperature and precipitation, particularly around the Pacific and Indian oceans (Ropelewski et al., 1987). However, the peri-Atlantic regions are also a concern, as the SOI index is associated with variability in sea surface temperatures and trade wind flows over the tropical Atlantic (Servain (1991); Zebiak (1993)). The positive phase of the +SOI index, manifested by a decrease in the zonal pressure gradient and trade wind flow, leading to persistent cooling in the central equatorial Pacific, result in a non-significant increase in all extremes on a regional scale. However, at a local scale, this positive phase, associated with cold waters in the eastern Pacific (Niña), lead to an increase in the total annual precipitation (PRCPTOT) and heavy precipitation (R95p) in Puerto Rico. It also lead to an increase in the number of rainy days (RR1), including the duration of wet sequences (CWD) in southern Haiti, as well as in the average intensity of precipitation per rainy day (SDII) and heavy precipitation (R95p) in southeastern Cuba. An increase in the duration of wet sequences (CWD) is also observed over the Saint-Dominque region. These results are in line with previous studies showing that a cold Pacific tends to favor precipitation in the Caribbean (Gimeno et al., 2011; Wu et al., 2011; Peterson et al., 2002).

5.2 Effect of sea surface temperature anomalies (TSA, SST-Car)

The evolution of temperature anomalies in the South Atlantic (TSA average over 0-20S, 10E-30W) and Caribbean Sea (SST-Car SST average 14-16N, 65-85W) presented in suppl. Fig. 3 are marked by increasing warming in the Atlantic and Caribbean Sea over the period 1985-2015. In the Caribbean, warming has intensified over the past three decades in both seasons (DJF and MAM) (suppl. fig.2). Thus, the +SST-Car phase in the Caribbean is associated with an increase in all extremes at the regional scale, apart from the mean rainfall intensity per wet day (SDII). Similarly, on a local scale, considering all islands, it lead to an increase in the number of consecutive rainy days (CWD), as well as in the number of consecutive rainy days on the island of Hispaniola (Haiti and Santo Domingo). The increase in heavy precipitation (R95p) in Puerto Rico, southeastern Cuba, and Haiti is also due to abnormally warm + SST-Car conditions in the Caribbean. These results are in line with previous research on the influence of sea surface temperature on precipitation in the Caribbean, particularly in the Greater Antilles (Wu et al., 2011), and on the link between sea surface temperature and extreme precipitation indices. For example. It has been shown that the average rainfall intensity per wet day (SDII) averaged over the Caribbean has a strong correlation with the warm phase of the Caribbean Sea (Peterson et al., 2002a). In contrast, the positive +TSA phase (mean TSA over 0-20S, 10E-30W) is associated with warmer sea surface temperatures (SST) in the southern tropical Atlantic (TSA), leading to a southward shift of the ITCZ (Philander et al., 1996) and a weakening of the southeast (SE) trade winds (Schneider et al., 2014; Nobre and Shukla,1996). This warm phase influences the precipitation indices over the Greater Antilles, notably the average daily precipitation intensity (SDII) over the entire region. The same regions, including Puerto Rico, were affected by an increase in heavy precipitation (R95p). In Haiti, the effect is more concentrated on the northwest coast. It is most pronounced in northern Haiti and southeastern Cuba. Similarly, total annual precipitation (PRCPTOT) and heavy precipitation (R95p) in Puerto Rico and Jamaica. These results are compared with those of a previous study (Utida et al., 2019) in which a correlation was found between TSA and precipitation data (rainy season) from CRU TS3.24(Harris et al., 2014). The results show that the warm phase of the TSA influences precipitation in southeastern Cuba and Jamaica. However, the effect is negative over Hispaniola and Puerto Rico. These results confirm that southeastern Cuba and Jamaica were influenced by TSA. The negative effect on Hispaniola could be explained by a less efficient estimation (CRU TS3.24(Harris et al., 2014)) of precipitation due to a grid resolution influenced by topography.

5 Conclusion

This work provides a relevant analysis of the evolution of extreme precipitation and its link with global teleconnections over the Caribbean, particularly the Greater Antilles, over the period 1985-2015. Extreme precipitation indices (PRCPTOT, RR1, R95p, CWD, and CDD) defined by the World Meteorological Organization Expert Team on Climate Change Detection and Indices (ETCCDI) were calculated. Next, the links between large-scale SST oscillation indices (NAO, SOI, TSA, and SST-CAR) and extreme precipitation indices (PRCPTOT, RR1, R95p, CWD, and CDD) were evaluated and tested using Spearman's correlation coefficient. The results show that warming in the southern tropical Atlantic (TSA), the Caribbean (mean SST-Car SST 14-16N, 65–85 W), and cooling in the eastern Pacific (Niña) have positive and significant effects on extreme precipitation indices. However, the significant effects on extremes were greatest at the island scale in the Greater Antilles. For example, in southeastern Cuba and Puerto Rico, there was an increase in heavy precipitation (R95p) and average rainfall intensity per wet day (SDII) associated with the positive phase of the indices (SOI, TSA, and SST-Car), whereas in Jamaica and northern Haiti, there were only two indices (TSA and SST-Car). The number of rainy days (RR1) and the maximum duration of consecutive rainy days (CWD) showed a significant upward trend over southern Haiti and the Dominican Republic, in line with the positive phase of the Southern Oscillation (SOI) and warming east of the Caribbean Sea surface.

These results further improve our knowledge of the impact of certain global teleconnections on extreme precipitation in the Greater Antilles. They also highlight the most relevant teleconnection indices (SOI, SST-Car (average SST-Car SST 14-16N, 65–85 W), and TSA) to be considered as part of the impact study in the region, to limit damage to key economic sectors such as agriculture, biodiversity, health, and energy.

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6 Author contribution

Conceptualization: C.D, A.D, S.A; methodology: C.D, A.D, S.A; Original draft preparation: CD; review and editing: all the authors.

7 Competing interests

The authors of this paper declare that they have no conflicts of interest.

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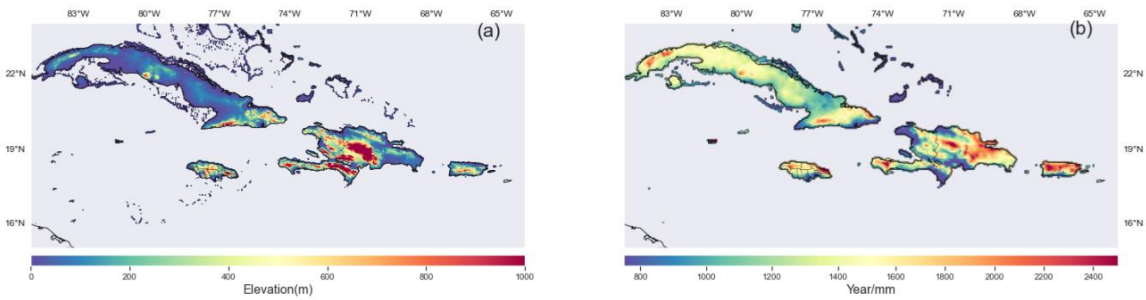

Figure 1. Location of study area. The figures show (a) the altitude of the four islands making up the Greater Antilles and (b) average annual rainfall.

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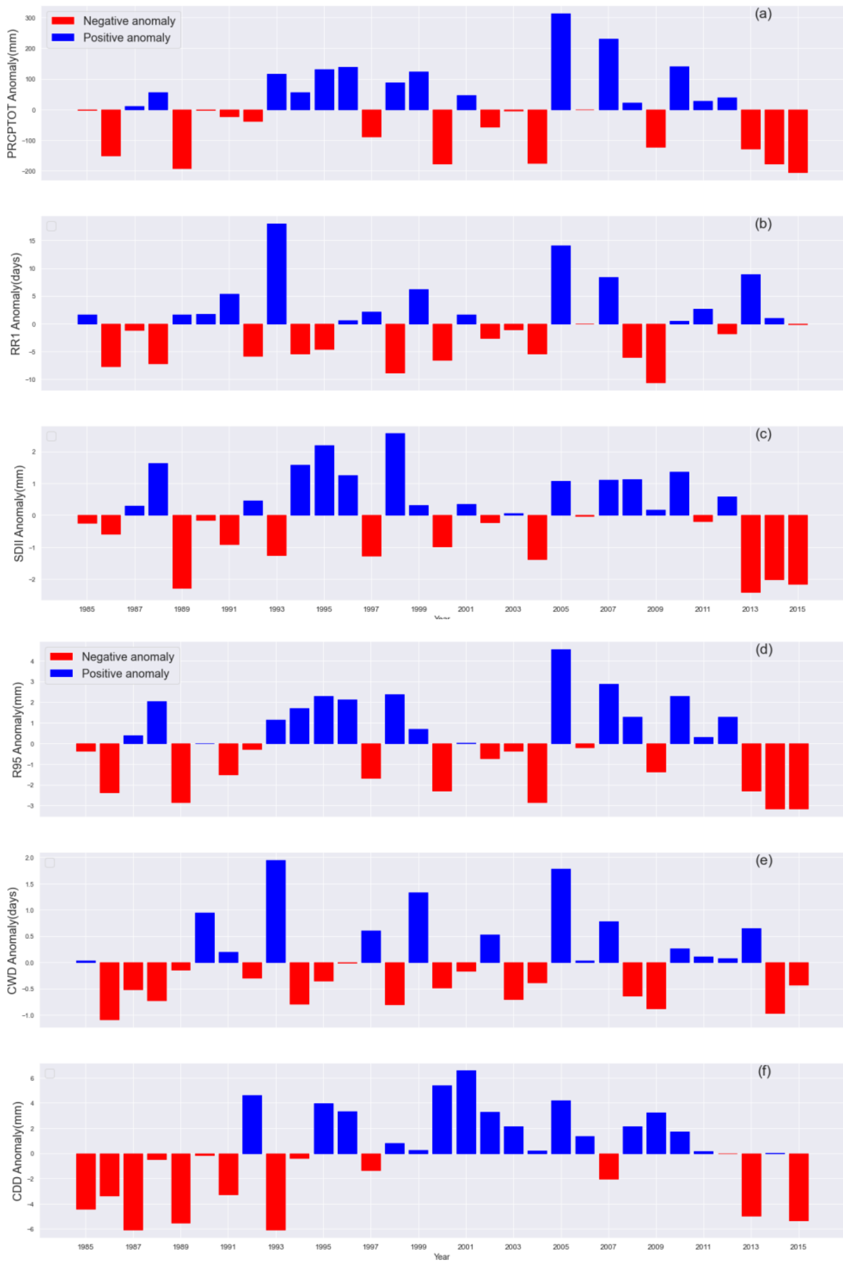

Figure 2. Interannual variability of precipitation indices in the Greater Antilles over period 1980-2015 with (a) PRCPTOT, (b) RR1, (c) SDII, (d) R95; (e) CWD; (f) CDD.

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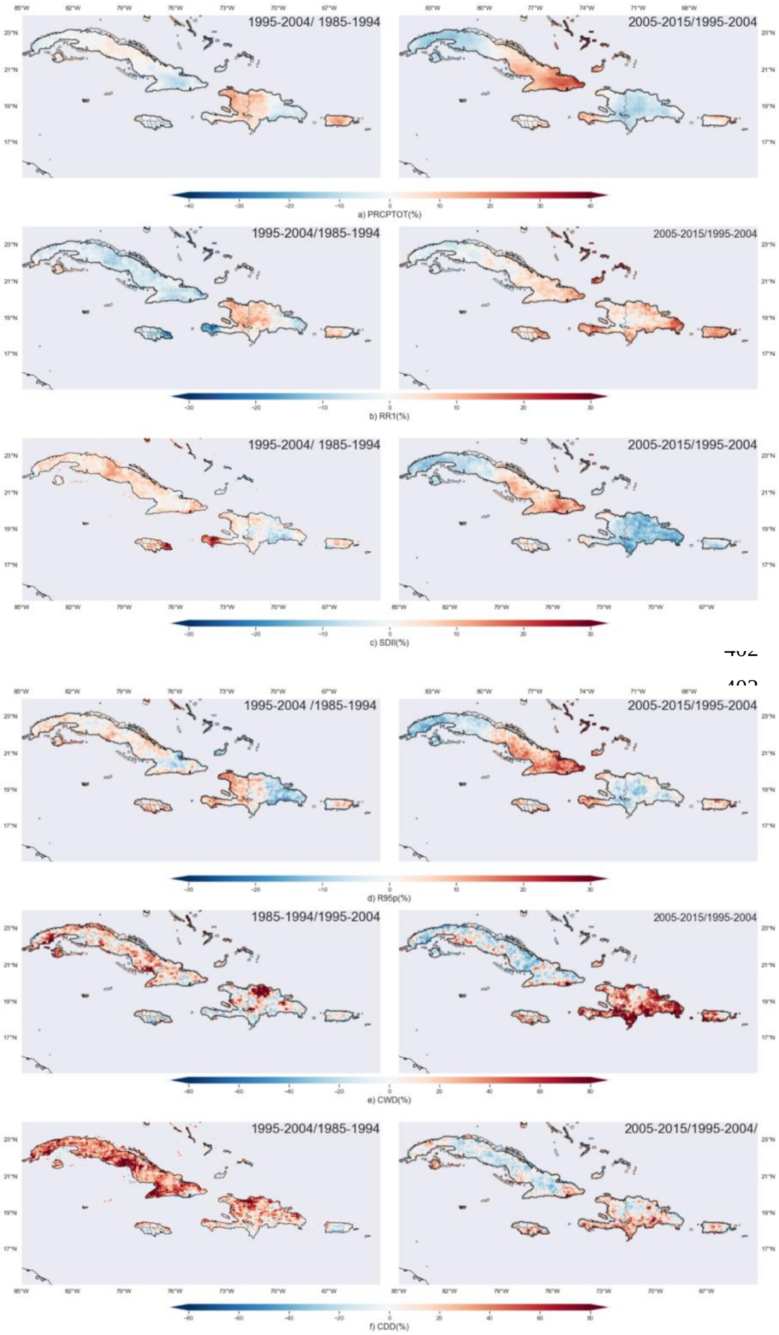

Figure 3. Annual change (%) between two decades of precipitation indices over the Greater Antilles (left: 1995-2004 compared to 1985-2015; right: 2005-2015 compared to 1995-2004 right): (a) PRCPTOT, (b) RR1, (c) SDII, (d) R95p, (e) CWD (f) CDD.

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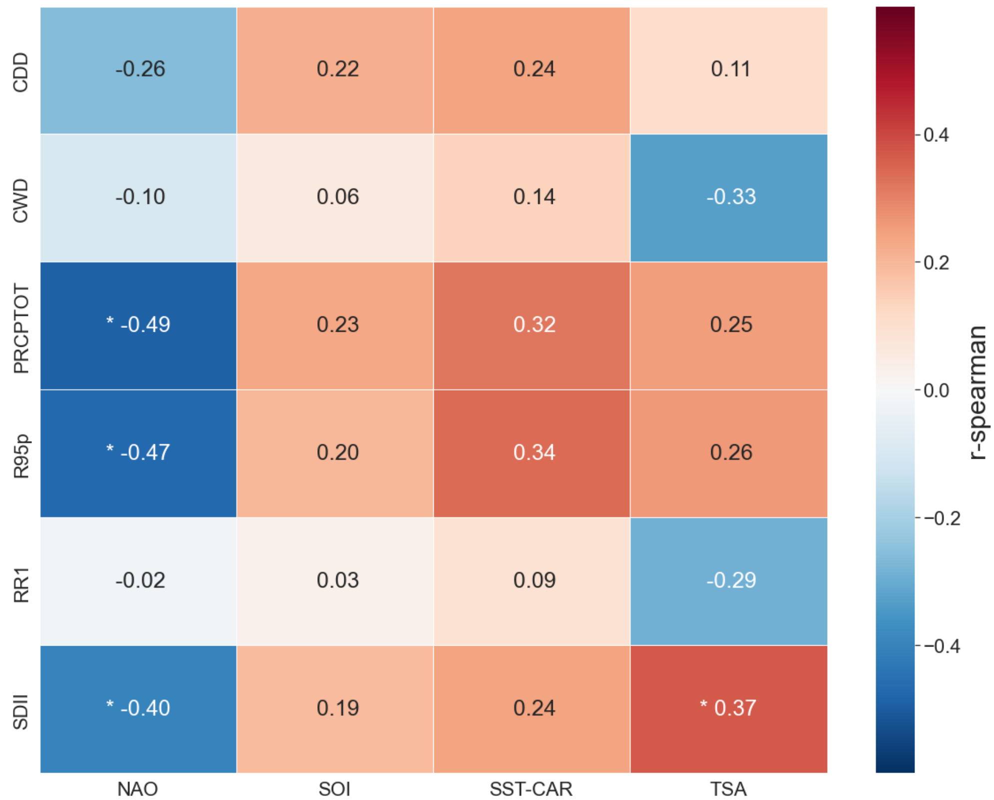

Figure 4. Correlation between precipitation indices and large-scale SST in the Greater Antilles (1985-2015). The values in table are the correlation coefficients of large-scale SST with extremes. The indices on the abscissa are the precipitation extremes and those on the ordinate are the SST indices. The symbol (*) represents a statistically significant correlation at a threshold less than or equal to 0.05.

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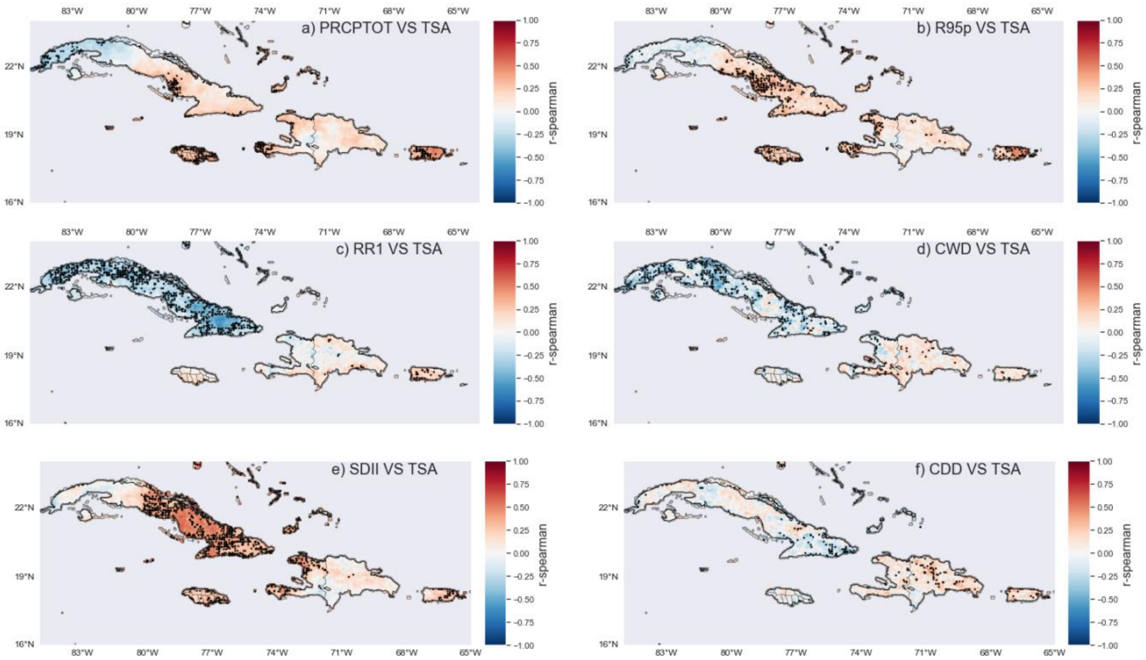

Figure 5. Correlation between precipitation indices and Tropical Southern Atlantic Index (TSA). The spatial correlation of extremes with TSA (SST average over 0-20S, 10E-30W) for this figure is presented in two columns; the first is realized with the indices: a) PRCPTOT Corr. TSA, b) RR1 Corr. TSA, c) SDII Corr. TSA and the second column with the indices: b) R95p Corr. TSA, d) CWD Corr. TSA, f) CDD Corr. TSA. Black dots represent areas where correlations are statistically significant at $p < 0.05$.

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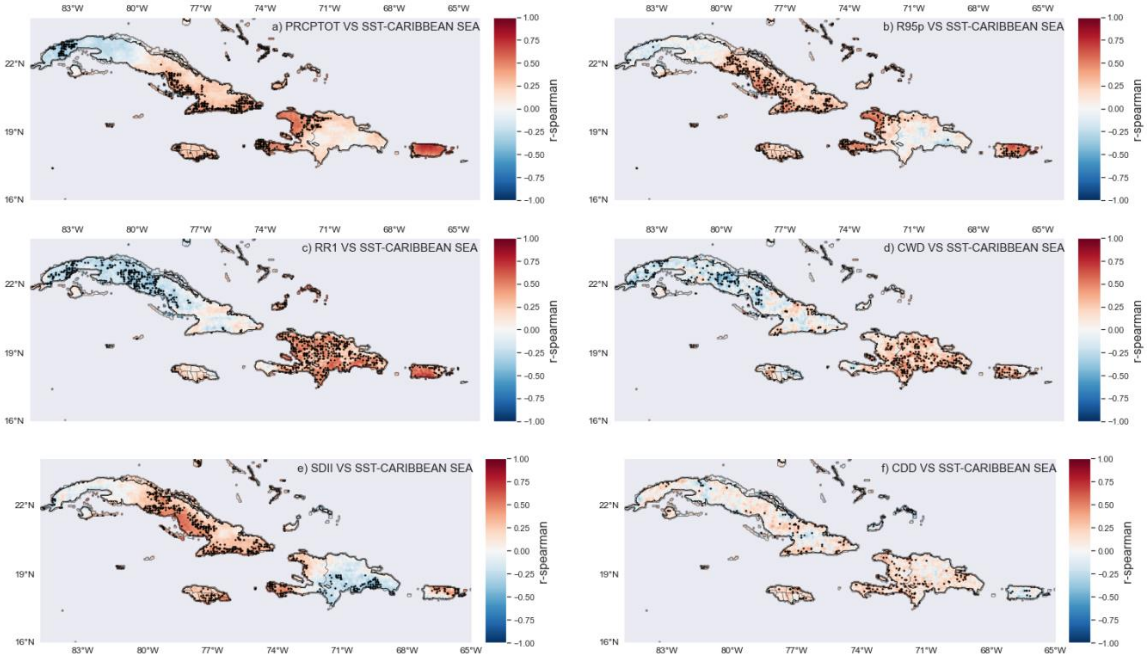

Figure 6. Correlation between precipitation indices and Caribbean Sea surface temperature. The spatial correlation of extremes with SST-Car(SST average 14-16N, 65-85W) for this figure is presented in two columns; the first is realized with the indices: a) PRCPTOT Corr. SST-Car, b) RR1 Corr. SST-Car, c) SDII Corr. SST-Car and the second column with the indices: b) R95p Corr. SST-Car, d) CWD Corr. SST-Car, f) CDD Corr. SST-Car. Black dots represent areas where correlations are statistically significant at $p < 0.05$.

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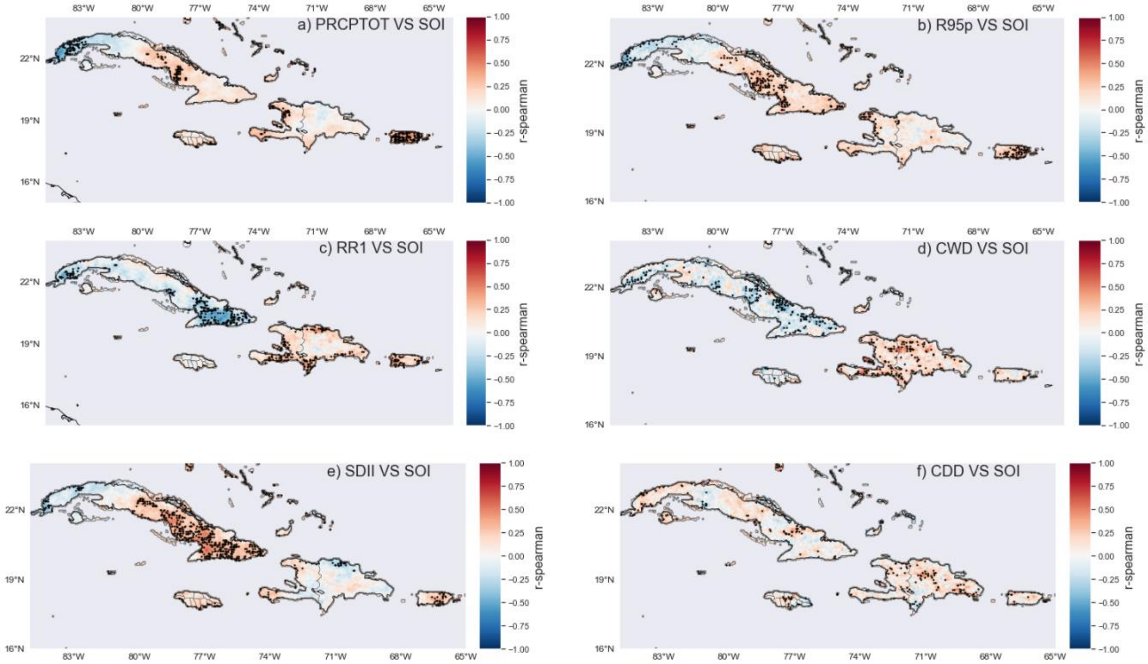

Figure 7. Correlation between precipitation indices and Southern Oscillation indices (SOI). The spatial correlation of extremes with SOI for this figure is presented in two columns; the first is realized with the indices: a) PRCPTOT Corr. SOI, b) RR1 Corr. SOI, c) SDII Corr. SOI and the second column with the indices: b) R95p Corr. SOI, d) CWD Corr. SOI, f) CDD Corr. SOI. Black dots represent areas where correlations are statistically significant at $p < 0.05$.

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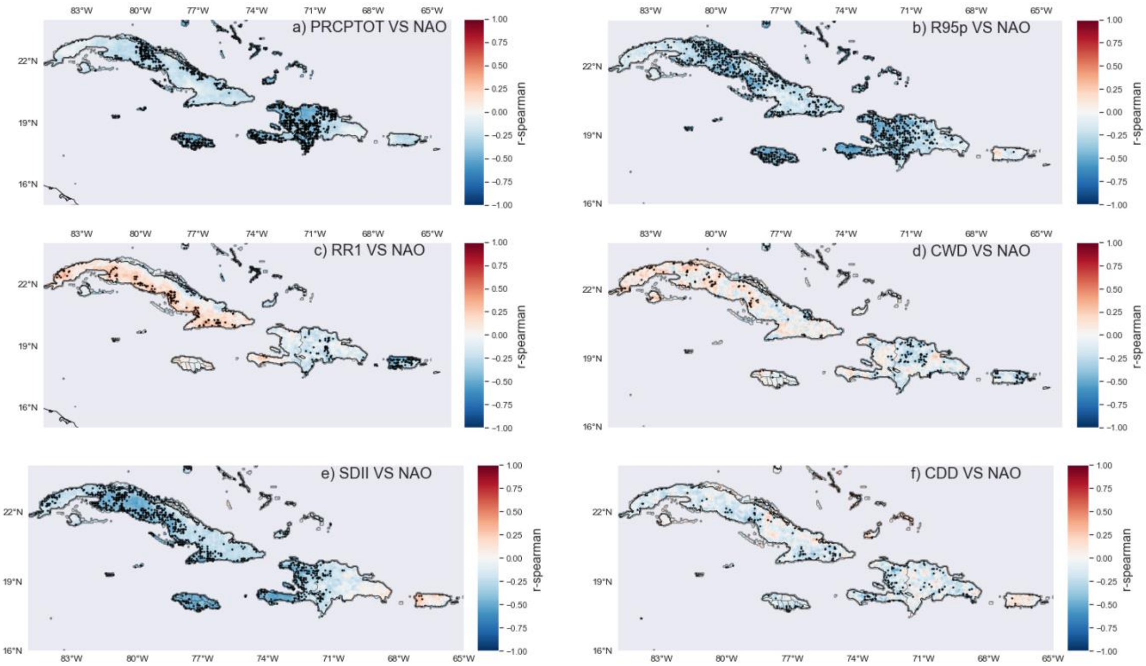

Figure 8. Correlation between precipitation indices and North Atlantic Oscillation Indices (NAO). The spatial correlation of extremes with NAO for this figure is presented in two columns; the first is realized with the indices: a) PRCPTOT Corr. NAO, b) RR1 Corr. NAO, c) SDII Corr. NAO and the second column with the indices: b) R95p Corr. NAO, d) CWD Corr. NAO, f) CDD Corr. NAO. Black dots represent areas where correlations are statistically significant at $p < 0.05$.

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Table 1 Precipitation indices

ID	Index Name	Indices definition	Units
RR1	Wet days index	Number of wet days ≥ 1mm	days
PRCPTOT	Annual total wet day precipitation	Annual total rainfall ≥ 1mm	mm
SDII	Simple daily rainfall intensity index	Annual total precipitation divided by the number of wet days (defined as precipitation ≥ 1.0 mm) in the year	mm/days
CWD	Consecutive wet days	Maximum number of consecutive days with daily rainfall ≥ 1mm	days
CDD	Consecutive dry days	Maximum number of consecutive days with daily rainfall < 1mm	days
R95p	Very wet days.	Annual total PRCP when RR>95th percentile.	mm