



The Role of Tropical Cyclones on the Total Precipitation in Cuba during the Hurricane Season from 1980 to 2016

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Abstract: This study quantifies the amount of rainfall supplied by tropical cyclones (TCs) to Cuba. It uses the long-term global gridded Multi-Source Weighted-Ensemble Precipitation (MSWEP) v2 data set, with a resolution of 0.1° in latitude and longitude, and a temporal resolution of 3 h during the hurricane seasons from 1980–2016. During this study period, 146 TCs were identified within a 500-km radius of Cuba. The contribution of TCs to the total precipitation over Cuba during the cyclonic season was ~11%. The maximum contribution occurs in October and November, representing 18% and 28% of the total precipitation, respectively. The interannual precipitation contribution shows a positive correlation (~0.74) with the number of TCs, but without a significant trend for the period. A climatological spatial analysis of the rainfall associated with TCs revealed great heterogeneity, although the major contribution was observed along the southern coast of the eastern and central provinces of Cuba, and in the western province of Pinar del Río. No significant difference was observed between the number of TCs that affected Cuba and their rainfall contribution under the positive and negative phases of the El Niño Southern Oscillation. However, the negative phase of the NAO led to an increase in the genesis of TCs that later affected Cuba, which led to a greater contribution to precipitation compared to that obtained from TCs during the positive phase of this oscillation. Our results also confirm that anomalous warmth of the tropical Atlantic Ocean, revealed through the Atlantic Meridional Mode, and enlargement of the Atlantic Warm Pool, enhances the genesis in the North Atlantic Basin of the TCs that affect Cuba, which was associated with an increase of the rainfall contribution to the total precipitation compared to that calculated for TCs formed during the opposite phases.

Keywords: tropical cyclones; rainfall contribution; teleconnection

1. Introduction

Tropical cyclones (TCs) are one of the most destructive atmospheric systems on the planet. The strong winds, storm surges, and heavy rains associated with these systems usually cause severe damage to ecosystems, agriculture, economies, and even human life in many regions, but particularly in the most vulnerable countries [1,2]. Despite this, the rainfall associated with TCs can play a positive role as a source of fresh water, even becoming the most important factor in increasing the level of dams and other surface water deposits [3]. Therefore, TCs are the most important weather phenomena



in the hydrological cycle for tropical and semiarid regions around the world [4]. For instance, several studies have shown that TCs' contributions to seasonal or annual rainfall can be up to 50% in some continental regions, depending on the characteristics and evolution of the wind field, topographic effects, atmospheric humidity, and size. This is mainly due to the proximity of these systems to the coastline [5–7].

Based on rain gauge observations, several studies have obtained the rainfall contributions of landfalling TCs for regions such as southeastern North America and surrounding islands [8–12], the coasts of Northern Australia [13,14], the Northwestern Pacific [15], and Mexico [2,16]. Prat and Nelson [17] performed the same analysis at global scale, but focusing on particular regions such as the southern region of the United States, the Caribbean region, and the Gulf of Mexico [18]. Also, Jiang and Zipser [7] showed that the TC rainfall contributions were 8–9%, 7%, 11%, 5%, 7–8% and 3–4% in the North Atlantic, East Central Pacific, Western North Pacific, Northern Indian Ocean, Southern Indian Ocean and South Pacific, respectively. In addition, some studies have used the Tropical Rainfall Measurement Mission (TRMM) multisatellite dataset to evaluate TC rainfall contributions [17–19].

The Caribbean, Central America and North America are regions particularly prone to tropical cyclone (TC) damage each year. Consequently, some studies have evaluated the contribution of TCs to the atmospheric branch of Middle America's hydrological cycle. The findings of Xu et al. [20] revealed that TCs provide approximately 14% of the total moisture transport to the North American coast. Shephard et al. [21] found that TC rainfall accounted for 8% to 17% of cumulative rainfall at different locations along the coastal zone of the southeastern United States. Years later, Knight and Davis [9] found this figure to be 5–10%, while Kunkel et al. [10] limited it to 6% in the same region. In the most recent studies, Prat and Nelson [7] showed that 15–20% was attributable to TCs along the southeastern United States coast, and 8–12% at 150–300 km from the coast. In addition, TCs contribute 20–60% to seasonal rainfall in coastal regions of Mexico [22,23], exceeding 20% along the southwest coast during summer [16], and up to 50% during the seasonal rainfall over semiarid regions [2]. For Puerto Rico, the maximum TC contributions are in August (20%) and September (30%) [12].

For a disturbance to develop into a TC, certain oceanic and atmospheric conditions must occur. For more than fifty years, it has been accepted that Sea Level Pressure (SLP) anomalies over the tropical Atlantic correlate with TC activity [24]. However, there are also studies that indicate that TC activity is related to climatic variability controlled by the Atlantic Meridional Mode (AMM) [25] and the El Niño Southern Oscillation (ENSO) [26]. Furthermore, some studies (e.g., [27,28]) suggest that the North Atlantic Oscillation (NAO; [29,30]) affects TCs, with the negative NAO affecting the western region of the high subtropical North Atlantic, which allows TCs to become recurring. Furthermore, it is known that the strengthening of the Atlantic Warm Pool (AWP) has an impact on the upper level wind change, reducing the vertical wind shear in the troposphere, which favours the formation and intensification of hurricanes from August to October [31]. All these anomalies cause changes in certain variables that affect cyclogenesis and, therefore, the rainfall associated with tropical cyclones.

Specifically, the behaviours of the Sea Surface Temperature (SST) anomaly patterns associated with different modes of climate variability either favour or disfavour TC genesis. During the negative phase of ENSO, known as La Niña, positive SST anomalies occur over the Caribbean Sea and the tropical Atlantic, while negative anomalies occur across the tropical eastern Pacific and extratropical Atlantic Ocean, this pattern contributes to TC genesis. The reversed pattern occurs during El Niño, the positive phase of ENSO, and the genesis of TC is inhibited [32]. On the other hand, the positive (negative) SST anomalies observed over the tropical Atlantic during the negative (positive) phase of the NAO provide favourable (unfavourable) conditions for TC activity. Warmer (cooler) SSTs over the central and western Atlantic during the positive (negative) AMM activate favourable (unfavourable) conditions for TC activity [33].

One of the zones most vulnerable to the impact of TCs is the Caribbean region. Cuba, in particular, is affected by several precipitation generating systems, with tropical cyclones occurring from June to

November. Several studies have been carried out on this subject. In 2013, Cordova et al. [34] identified the TCs that affected the province of Ciego de Ávila, located in the middle of the island, from 1851 to 2013. In this study, a climatological description of these tropical systems was made, the distribution function was found that best fitted the series used, and return periods for tropical cyclones, hurricanes, and major hurricanes were calculated. In the same year, Hidalgo et al. [35] carried out a climatological study of tropical cyclones in the Holguín province. Sacasas [36] studied the danger of cyclones in Cuba using a geographic information system, and, more recently, González and Ramos [37] determined a chronology of tropical storms and hurricanes that affected Havana. Marcelo and Rodriguez [38] identified the hurricanes of the North Atlantic that affected the provinces of Artemisa, Havana, and Mayabeque between 1791 and 2018. In all these investigations, the rainfall contributions of TCs were not addressed. Considering that the economic success of the Caribbean region, in particular Cuba, is highly dependent on freshwater supplies, particularly for agriculture and tourism [39], the aim of this work is to quantify the amount of rainfall supplied by TCs, using a long–term gridded precipitation dataset, and to investigate the roles of oceanic and atmospheric teleconnections on the variability and trends of the TCs' effects and their variations in rainfall contribution.

Region of Study

Cuba is the largest archipelago in the Caribbean region (Figure 1a), with an area of 109,886 km², including 9969 km² of islands, islets, and cays. The largest island, long and narrow, is also named Cuba; it is 104,556 km² in area [40], and characterised by predominantly low relief, with low–altitude mountain systems located in the southeast and centre of the country (Figure 1b). Regarding the administrative organisation, the country is divided into 15 provinces, as well as a special municipality named Isla de la Juventud (the second largest island).



Figure 1. Geographic location of Cuba in the Caribbean region (**a**). The elevation is shaded in greenbrown (in meters above sea level) from the HydroSHEDS project [41]. The boundaries of the 15 provinces of Cuba are delimited by black lines (**b**).

Due to its location in the tropical zone, very close to the Tropic of Cancer, Cuba receives high levels of solar radiation that determine its warm climate. However, the Cuban archipelago is also located under the influence of the trade winds and high relative humidity imposed by the North Atlantic Subtropical Anticyclone, which is the main climate modulator system for the archipelago [42]. Therefore, the climate of Cuba is characterised by two main hydroclimatic periods, a rainy season from May to October, and a period of little rain from November to April, known as the dry period [43].

The rainy season exhibits a bimodal mode, with two rainfall maxima in May–June and September–October, separated by two months with less rainfall (July–August), which has been termed by several authors as the 'midsummer' drought [44,45]. A similar annual cycle has been described using observational datasets by Alvarez et al. [46] and Cabrera and Zuaznábar [47].

2. Data and Methodology

2.1. Datasets

The Atlantic hurricane database (HURDAT2) was used to determine the TCs that affected Cuba in the period 1980–2016. This dataset is in text format, with information every six hours on the location, maximum wind speed, and minimum central pressure of all known tropical and subtropical cyclones [48]. This database is freely available from the National Hurricane Center at [49].

In the absence of long-term and high temporal resolution precipitation data from gauge stations, data from the Multi–Source Weighted–Ensemble Precipitation (MSWEP) v2 [50] were used; these data have a regular latitude/longitude grid of $0.1^{\circ} \times 0.1^{\circ}$, and 3–h temporal resolution for the period 1980–2016. This database incorporates a wide range of data from different sources. In addition, its authors have computed a correction for systematic terrestrial precipitation biases due to gauge undercatch, using observed river discharges from 13,762 catchments worldwide and daily observations from 76,747 gauges across the globe. According to these authors, increasing the spatial resolution from 0.25° [51] to 0.1° enables more detailed terrestrial hydrometeorological studies for high–water–yield mountainous regions, coastal areas, and small islands. MSWEP v2 data are freely available upon request at [52].

To assess the relationship between atmospheric and oceanic teleconnections and the number of TCs that affected Cuba during the study period, we considered the ENSO, NAO, and AMM indices. These modes of variability are known to induce large–scale control of tropical Atlantic cyclonic activity [33,53,54]. The Bivariate El Niño Southern Oscillation Index (BEST) [55] was used to represent the ENSO conditions. Some indices to identify the occurrence of ENSO events are based solely on SST data, or solely on the atmospheric component. BEST, however, has the advantage of combining the Niño 3.4 SST index and the Southern Oscillation Index (SOI). The alternative (less stringent definition) table of months freely provided at [56], was used. The NAO index values used were obtained from the Climate Prediction Center (CPC) at [57]. According to the information offered by the CPC, the NAO is obtained through a rotated principal component analysis (RPCA) [30], using the monthly mean standardised 500 mb height anomalies from the NCEP/NCAR Reanalysis for the region of 20–90° N. The monthly climate time series of the AMM index [25] is available at [58]. To determine the negative, neutral, and positive phases of the NAO and AMM, we used the approach of Patricola et al. [59] and Muñoz and Rodrigo [60]. The phase of the phenomenon is positive (negative) when the index value is greater (less) than the standard deviation of the series in the study period.

The area of the Atlantic Warm Pool (AWP) was also used to determine its possible influence on the number of TCs that affected Cuba, and its contribution to the total precipitation. Following Wang and Enfield [61,62], the AWP was defined as the oceanic area with a Sea Surface Temperature (SST) greater than 28.5 °C in the tropical North Atlantic region. We chose the zone between 2° N and 32° N, and from 30° W to the American coast. The AWP area was calculated for every month from May to November for the period 1980–2016. We used the monthly values of SST from the Centennial in situ Observation–Based Estimates (COBE)dataset [63–65], with a horizontal resolution of 1° in both longitude and latitude. This dataset is freely provided by the NOAA/OAR/ESRL PSL, from their web site at [66].

2.2. Methodology

Identification of TCs that Affected Cuba

We consider that a TC affected Cuba if, in its trajectory, the centre of the system was within 500 km of the coast. The reason for choosing this criterion is that it is consistent with the range of the TC primary wind circulation region (80–400 km radius) and with the range of the curved TC cloud shield (550–600 km radius) [22]. Numerous studies have also implemented a radius of ~500 km for the same purpose, for regions such as México [22], Central and North America [2], China [67], or for the six main cyclogenetic basins globally [7]. However, according to Prat and Nelson [17], the total precipitation within the 500 km radius can also be influenced by rainfall from fronts or troughs. The criterion already explained was used to determine the total rainfall contributions of TCs during the months of the hurricane season, from June to November, for the period 1980–2016. Statistical analysis (frequency and trends) was performed for the total number of TCs found, as well as considering different TC categories. TCs are denoted as tropical depressions if winds are less than 17 m/s, as tropical storms (TS) if they range from 18 to 32 m/s, and as hurricanes (HU) if winds are higher than 33 m/s [68].

To establish the relationship between the occurrence of TCs and the climatic teleconnections for the NATL basin, we counted the number of systems formed in each phase of the ENSO, NAO, and AMM during the period of study. A composite analysis was performed to quantify the average TC rainfall contribution during the months under the positive, neutral, and negative phases of these modes. We determined the anomalies of the mean area of the AWP for each season in the study period 1980–2016, taking into account the climatological value of the AWP area (\sim 4.4 × 106 km²); when the anomaly exceeded this value by 25%, the AWP was considered large, and when the anomaly was smaller by 25% the AWP was considered small; otherwise it was neutral [54]. The kernel density estimation (KDE) was used for the behaviour analysis of TCs trajectories. This is a nonparametric method to estimate the probability density function (PDF). A smoothing function and a bandwidth value that controls the smoothness are the key principles of KDE. In this research, bandwidth was used according to Scott's Rule [69].

3. Results

3.1. TC Activity During the Rainy Season in the Period 1980-2016

In the cyclonic season, a total of 564 systems were formed in the NATL basin during the period studied. According to the criterion used here, Cuban territory was affected by a total of 146 systems, with a maximum in 2005 (12 TCs), followed by 1988, 2008 and 2010 with seven TCs each; in 1983, 1989 and 1997 only one TC occurred each year (Figure 2a). The name of each TC that affected Cuba during each month of the cyclonic season in the period 1980–2016, appears in Table S1 of the Supplementary Material. The percentages of the total number of systems annually that affected Cuba were also calculated. These varied from 6% in 1989 to 46% in 1996, with an average of about 25% (Figure 2b). The effects of these systems can be direct or indirect; direct effects occur when the centre of the system crosses the Cuban mainland, and indirect effects occur when the system moves close to Cuban territory (~500 km) and the spiral bands produce rains over the country. The PDF calculated with the trajectories of the TCs that affected Cuba during each month is shown in Figure 3, and illustrates the most frequent path of TCs. In June the most intense PDF is observed over the Gulf of Mexico, reaching the west of Cuba (Figure 3a). In July, August and September, the TCs tend to surround the island to the north (over Bahamas) and south (across the Caribbean Sea) (Figure 3b–d). Finally, in October and November, the most frequent TCs pathway occurred over the central and west Caribbean Sea (Figure 3e,f).



Figure 2. (a) Total number of tropical cyclones (TCs) formed in the whole North Atlantic Ocean basin (blue bars), and those that affected Cuba (red bars). (b) Percentage of TCs that affected the Cuban mainland. Period: June to November 1980-2016.



Figure 3. The probability density function (PDF) (10^{-3}) for single trajectories of TCs that affected Cuba during: (a) June, (b) July, (c) August, (d) September, (e) October and (f) November. Period: 1980–2016.

Figure 4a shows the number of systems that affected Cuban territory, separated into those that made landfall (35 TCs) and those that did not (111 TCs), representing 24% and 76%, respectively. It is notable that in 2008 four TCs made landfall (Gustav, Ike, Paloma and Fay) with trajectories that affected most of the Cuban territory, causing extensive economic losses, mainly in the western region [70–72]. Another remarkable year was 2002, with three TCs (Lili, Isidore and Hanna) that had their trajectories in the Caribbean Sea, affecting the western provinces from Pinar del Rio to Matanzas. During the remaining seasons, there were one, two, or no systems with landfall on Cuban territory.

Using the Atlantic hurricane database (HURDAT2) with a 6–h temporal resolution, the TCs were categorised according to wind intensity along each trajectory Figure 4b shows the number within each category (Tropical Depression (TD), Tropical Storm (TS) and Hurricane (HU)) that affected Cuba. The maximum impact on Cuba during the study period was caused by TS, with a maximum of 561 6 h occurrences, followed by TD and HU with 331 and 303 6 h occurrences, respectively.



Figure 4. (a) Numbers of TCs that made landfall in Cuba (red bars), and that did not make landfall but came within 500 km (blue bars). (b) Numbers of TCs in each category (Tropical Depression (TD), Tropical Storm (TS) and Hurricane (HU)) affecting Cuba along their trajectories, accounted every 6 h. Period: 1980–2016.

3.1.1. Relationship between TC activity and ENSO, NAO, AMM and AWP

According to Lim et al. [33], seasonal cyclonic activity in the NATL basin can be modulated as a combination of the three modes of variability, ENSO, NAO, and AMM, including substantial amounts of the variability of certain fields such as sea level pressure, upper–level geopotential height, vertical wind shear, and relative humidity over the North Atlantic. It is therefore important to assess the teleconnection impacts of these modes of climate variability on the TC activity that affects Cuban territory. We also considered assessing the impact of the AWP, which has been proven to play an important role in the cyclonic activity and climate of the western hemisphere [54,63,64].

Figure 5 illustrates the PDF for the TC trajectories that reached Cuba formed during the positive, neutral and negative phases of ENSO, NAO, AMM, and larger and smaller AWP. In general, the TC trajectories surround the Caribbean islands to the north and south. In the El Niño phase, the greatest density was observed towards the northeast and very close to the Bahamas, revealing a predominant northward and returning direction (Figure 5a). The density pattern changed during La Niña when the region of maximum density was observed in the Western Caribbean Sea (to the north of Honduras and Nicaragua), with a secondary band of high density along the Caribbean islands (Figure 5c). During the positive and negative phases of NAO (Figure 5d,f) the density patterns of TCs showed a northwest-southeast seesaw. During the positive phase, the region of higher density was located close to the west of Cuba, revealing that the TCs follow a path to the northwest. On the contrary, during the negative phase the density of the trajectories is higher to the east and south, affecting the east of Cuba. The density patterns during the positive and negative AMM (Figure 5g,i) revealed an opposite pattern compared with the behaviour during the NAO phases. Between both AMM phases the trajectories differ substantially; during the positive phase, the greatest number of TCs travelled in a west direction through the Caribbean Sea along southern Cuba, but during the negative phase, the major density was observed to the north over the Peninsula of Florida and the Atlantic Ocean along the eastern coast of the United States, affecting only those Cuban provinces located in the west of the island. Finally, the density pattern shown in Figure 5k, l revealed that during the neutral

and the smaller AWPs the TCs that affected Cuba predominantly moved along southern of Cuba through the Caribbean Sea, with a northward pathway to the Gulf of Mexico and then turn northeast, affecting western Cuba.



Figure 5. Density (10^{-3}) of TCs trajectories that affected Cuba during the positive, neutral and negative phases of El Niño Southern Oscillation (ENSO) (**a**–**c**), North Atlantic Oscillation (NAO) (**d**–**f**), Atlantic Meridional Mode (AMM) (**g**–**i**), and larger and smaller Atlantic Warm Pools (AWPs) (**j**–**l**). Period: 1980–2016.

Figure 6 illustrates the number of systems that affected Cuban territory under positive, negative and neutral phases of the ENSO, NAO, AMM and the larger, neutral, and smaller AWP, as well as a summary of this information as percentages. Our results (Figure 6b) show that 65.07%, 17.81% and 17.12% of the TCs that affected Cuba were formed during the neutral, positive and negative phases of the ENSO, respectively. Despite this finding, Figure 6a also reveals that the years with major effects in terms of the number of systems were 2005, 1995, 1996, 1999 and 2001 during neutral phases, 1988 and 2010 for negative conditions, and 2004, 1987 and 2002 for positive ones. The number of systems that affected Cuba under the different phases of the NAO is shown in Figure 6c. The systems formed in the neutral phase were most likely (73.29%), but more systems affected Cuba during the negative phase than during the positive phase (17.12% vs. 9.59%) (Figure 6d). This fact may be associated with the greater number of TCs that form over, or reach, the western Caribbean across trajectories further south.

The numbers and percentages of TCs that affected Cuba during different AMM phases appear in Figure 6e,f. The AMM mainly prevailed under the neutral and positive phases, and in consequence both showed the maximum occurrence of TCs, the 71.92% of the TCs that affected Cuba were formed during neutral AMM conditions, 23.97% during the positive phase, and only 4.11% during the negative phase (Figure 6f). It is highlighted that the peaks observed in 2005 and 2010 were associated with a positive phase of AMM, and also during a larger AWPs (Figure 6g).

In the period 1980–1996, smaller AWPs prevailed, with a pair of normal (neutral) seasons, and a clear dominance of larger AWPs occurred from 2004 (see Figure 6g), resulting in a highest percentage of TCs during it (Figure 6h). The temporal evolution of the AWP area anomalies (AWP–AA) and the total number of TCs affecting Cuba is shown in Figure 7. The temporal evolution of the AWP–AA reflects a continuously increasing positive trend, more evident from 1994 onwards. This fact is of vital importance because within the AWP, the temperatures required for TC development extend to greater depth than elsewhere, thus reducing the tendency of a storm to diminish that potential by mixing cool subsurface water into the upper warm layer [54]. However, the correlation between the AWP–AA and the number of TCs per year was 0.39, and was above the 95% significance level; this is in agreement

with the correlation value of 0.33 obtained by Wang et al. [54], but they considered the total number of hurricanes in the NATL basin.



Figure 6. Left column: Number of TC systems during the different phases of ENSO (**a**), NAO (**c**), AMM (**e**) and AWP (**g**). Right column: Percentage of TCs during each phase of ENSO (**b**), NAO (**d**), AMM (**f**) and AWP (**h**). Period: 1980–2016.



Figure 7. Temporal evolution of the AWP area anomalies (AWP–AA) (discontinuous blue line), its trend (blue line), and the total number of TCs that affected Cuba (discontinuous green line). Dashed black lines show 25% of AWP–AA. The R value is the correlation coefficient between both series. Period: 1980–2016.

The difference by phase in the percentage of TCs between associated to ENSO, NAO, AMM, and AWP was checked in terms of significance applying a T-test, considering as null hypothesis that the average TCs affectation was the same for the positive and negative phases. Only significant differences were found between those TCs formed during large and small AWP and for positive and negative phases of the AMM (with a 95% and 90% of confidence, respectively).

3.2. Monthly Mean TC Rainfall and Its Contribution

The monthly precipitation for each rainy season, and for those that were associated with TCs, was calculated to obtain the contribution of these systems to the total monthly rainfall over Cuba. To do this, we considered the land grid points from the MSWEP precipitation dataset. Figure 8 shows the monthly mean precipitation over Cuba from June to November for the 37 years from 1980 to 2016, as well as the monthly mean rainfall attributed to TCs, and its percentage with respect to the total monthly values. The first month of the rainy season, June, is the rainiest season (186 mm) in Cuba. However, other studies using observational data [43] have found some heterogeneity in the annual cycle of precipitation across the country, with regions where the maximum precipitation occurs in June, and in others where it occurs in September. In June, the mean precipitation associated with TCs was 12 mm (a total of 15 TCs affected Cuba; see Table 1), representing around 6% of the total monthly mean precipitation. In the following two months (July and August), there was a reduction in precipitation; this period is known as the midsummer drought [44,45]. During this period, the contribution of TCs to the total precipitation was greater during August (\sim 15%) than in July, and the number of TCs affecting Cuba was also higher (39 vs. 19) (Table 1). In September and October, Cuba was affected by 32 and 28 systems, respectively. In these months, the rainfall associated with TCs was on average the highest of the rainy season, and the percentage contributions were 14% and 18%, respectively. Finally, November is characterised by lower precipitation (65 mm), but the 13 TCs provided rainfall representing 28% of the total precipitation that month. Table 1 gives a summary of the number of TCs, range of monthly total rainfall values across Cuba, TC-related rainfall, and its percentage contribution, for the period 1980–2016. These results are in agreement with Larson et al. [16]. Using observations from rain gauges, these authors found that 15% of the TCs contributions occurred along the U.S. Gulf Coast, and 20% along the Mexican coast during 1950–1998. Other results revealed that higher percentages occur on the southern coast of the Cuban mainland, and are associated with landfall TCs, similar to what occurs on the southeastern coast of the United States [17] with a range of contribution of 15–20%.



Figure 8. Monthly mean precipitation over Cuba (dashed blue line), the monthly mean precipitation attributed to TCs (continuous blue line), and the percentage that this represents (green bars). Data from Multi–Source Weighted–Ensemble Precipitation (MSWEP) for the period 1980–2016.

Table 1. Number of TCs that affected Cuba by month, range of total precipitation values across Cuba by month, range of rainfall associated with TCs across the country, and the percentage of these contributions. Period: 1980–2016.

	June	July	August	September	October	November
No. of TCs	15	19	39	32	28	13
Range of total rainfall (mm)	85-350	45-250	85–250	85–350	110–350	20-250
Range of precipitation of TCs (mm)	0.5–45	3–20	10–45	10-85	10–65	10–45
Range of the contribution of TCs to total precipitation (%)	0–15	55–10	5–25	5–25	10–33	10–50

Particularly to be noted is that in July, comparing to the preceding month, the monthly mean precipitation and the contribution from the TCs decreased, as Figure 8 shows. This fact is in agreement with the midsummer drought period [44,45]. However, an increase in the number of TCs affectations takes place (see Table 1). An important factor in determining this result could be the differences between the TCs trajectories (Figure 3). The pattern of density obtained from trajectories that affected Cuba in June shows a maximum ($>5 \times 10^{-3}$) over the western Caribbean Sea, the Channel of Yucatan, and the Gulf of Mexico, principally affecting the west of Cuba; which is in agreement with the location of the greater TCs rainfall contribution over the provinces of Pinar del Rio and Isla de la Juventud (~7.5–15%), in the west of Cuba (Figure 9m). The region with the highest density of trajectories in this month reveals a north-northeast direction, that is, perpendicular to the Cuban coast, which favoured the areas of rainfall associated with these TCs. On the contrary, the density pattern obtained for the TCs trajectories that affected Cuba during July (Figure 3b) shows a major dispersion, with maximum values over the eastern and western Caribbean Sea and the Bahamas, distant from Cuba. Therefore, the PDF over Cuba is just about 1×10^{-3} . In this month the TCs mainly formed over the North Atlantic (above 10° N) and the eastern Caribbean Sea, thus, they moved west–northwest, parallel and mainly distant from the southern and northern coasts of Cuba, implying that few TCs produced rainfall over the country. Consequently, a lower TCs rainfall contribution for July than in June was obtained, with values that do not exceed ~10%.



Figure 9. Mean total precipitation (**a**–**f**), mean total TC–related precipitation (**g**–**l**), and its percentage values (**m**–**s**) for June, July, August, September, October and November. Period: 1980–2016.

A spatial analysis was also performed to determine the variability of the TCs rainfall contribution across Cuban territory (Figure 9, and values in Table 1). Figure 9a shows the mean total precipitation for June, with values that oscillated between 85 mm and 350 mm (see Table 1). With respect to the TC contribution (see Figure 9g), the accumulated values range from ~ 1 mm up to approximately 45 mm observed in the western region, representing a contribution reaching 15%. These lower percentages are consistent with the lower TC activity during this month (see Table 1), and the fact that the accumulated precipitation values are more associated with instability and convective movements, and the medium-level trough, which causes large accumulations of rain in a few days [73]. For July (Figure 9b), the range of mean total rainfall was 45–250 mm, and for the TCs was 3–20 mm, representing 5% to 10% of the total. This month had a similar behaviour to June in the number of systems for all seasons (19), being insignificant compared to August, September, and October. For August, the mean total rainfall ranged between 85 and 250 mm (Figure 9c). The maximum rainfall associated with the TCs was observed in the western half of the country (from Ciego de Ávila to Pinar del Río) (see Figure 9i), and on the southern and northern coasts of the eastern provinces. This pattern expressed in percentages illustrates a high spatial differences, with values that vary between 5-25% (Figure 9o). The maximum contributions were observed in the eastern provinces of Guantánamo and Santiago de Cuba, in the central provinces of Ciego de Ávila and Sancti Spiritus, and in the western provinces of Matanzas and Pinar del Río. This result is consistent with previous studies on the Yucatan Peninsula, Florida and the Caribbean Islands, which found values of 7–20% [7].

The total mean accumulated rainfall in September ranged from 150–350 mm, revealing a very homogeneous pattern (Figure 9d). The rainfall associated with TCs fluctuated from 10 to 85 mm, showing high contribution values from 5% to 25% (Figure 9p). In October, the spatial pattern of

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precipitation varied between 110 mm and 350 mm (Figure 9e), of which 10–65 mm was attributed to TCs, which represents a contribution that ranges from 10% to 33%. The maximum contribution was observed near the south coast in the province of Cienfuegos and the southern part of Sancti Spiritus. This month was the third most affected in the June-November period, with 28 TCs. Finally, the month of November (Figure 9f) presented accumulated values from 20–250 mm, and TC–associated values that ranged from 10–45 mm. Taking into account that the mean precipitation and mean TC–associated rain for November differ only slightly, contribution values of 10–50% are reached, showing the maximum values in the province of Matanzas and the eastern part of Cienfuegos (see Figure 9s). This is related to the fact that this month constitutes the beginning of the dry season in Cuba [73], when overall rainfall decreases, and therefore the rainfall associated with TCs can represent a high percentage of the total.

The precipitation associated with the TCs depends mainly on two elements: the speed of translational and the direction of the trajectories. The path of a TCs is a determinant key for the distribution of the rainfall generated, with the heaviest rainfall occurring in a narrow swath close to the track of the TC [74]. The translational speed of a TC also plays an important role. Both create azimuthal asymmetries in the rainfall field [75]. Figure 10 shows the translational speed of all the TCs that affected Cuba during each month of the cyclonic season in the period 1980–2016. In this figure, the dashed red and black lines represent the average translational speed for each month and for the whole cyclonic season respectively. In June and July, the TCs that affected Cuba had translations speeds (8.5 m/s and 7.6 m/s, respectively) higher than the average obtained for the whole cyclonic season (7.3 m/s). For August, the average translational speed was 7.2 m/s, and 7.3 m/s for September and October. However, TCs that affected Cuba during November had a slower movement (6.6 m/s), and consequently a major impact on the country. This impact is evidenced by a greater contribution of precipitation in the central region of the country (Figure 8), in correspondence with the higher density values of the trajectories shown in Figure 3f.



Figure 10. Translational speed for each TC (blue dots) that affected Cuba for each month from June (**a**) to November (**f**), the average translational speed for the month (dashed red line) and the mean for June–November (dashed black line).

3.3. Seasonal Mean TC–Related Rainfall and Its Contribution to the Total

The analysis was further developed to consider the whole cyclonic season. Figure 11a shows that the mean total accumulation of precipitation ranged from 85 to 250 mm, with differences across the country, and values increasing from east to west. A similar geographical pattern is shown by the precipitation associated with TCs, but with lower values of 10 to 45 mm. In percentage terms, the TC contribution ranged between 5% and 25%, with TC–related precipitation having the greatest importance towards the west of Cuba and towards the southern coastlines, determined by the northward trajectories of the systems, and the orographic barrier. Mountain systems weaken TCs, and therefore most of the precipitation is on the windward side, and less on the leeward side.



Figure 11. Mean values of (**a**) total precipitation, (**b**) total TC–related precipitation, (**c**) percentage of TC–related precipitation with respect to the total. Period: June-November from 1980 to 2016.

3.4. Interannual Variability of TC Effects, and their Contribution to Total Precipitation

Figure 12 shows the temporal evolution of the number of TCs that affected Cuba every year from 1980 to 2016 during the cyclonic season (green dashed line) and their contribution to the total seasonal precipitation (blue dashed line). Both series illustrate high interannual variability, and a high correlation of 0.76, which is above the 95% significance level. This indicates that the percentage TC contribution is directly related to the number of systems that affect Cuba in each season; but it must be taken into account that this percentage depends on the total precipitation for the season, which is variable. Therefore, it may happen that in years with fewer cyclones (e.g., 2008), a greater contribution could occur. Both series reached common peaks in 1985, 1988, 1994, 1996, 2002, 2005, 2008 and 2010, and the contributions ranged from a minimum of 0.2% in 1983 to a maximum of ~30% in 2005. In Figure 12, the discontinuous red line represents the average TC contribution to precipitation in the period of study (~11%).

Another aspect to consider is the role of ENSO, NAO, AMM oscillations, and AWP in the variability of TC genesis, and therefore the number of TCs that affect Cuba and the magnitude of their effects. As Figure 12 shows, peak values of TCs occurred in 1988, 2005, 2008 and 2010. During these years, Cuba was mainly under the combined influence of a larger AWP and neutral–negative phases of the ENSO, mostly neutral–negative NAO conditions, and with an almost total predominance of positive and neutral AMM (Figure 5). Therefore, the possible modulation of these teleconnections may affect the temporal evolution of both the genesis of TCs and their impacts on Cuba. However, the trends of TC count and TC contributions do not show significant values for the period 1980–2016.



Figure 12. Temporal evolution of the total number of TCs (dashed green line), the rainfall percentage contribution of these systems (dashed blue line), the mean contribution (discontinuous red line), the trend of the contribution (continuous blue line), and the trend in TC count (continuous green line).

To better illustrate the relationship between the modes of climate variability and the rainfall contribution of TCs that affected Cuba, in Figure 13 the filled bars show the percentages of the number of TCs during each phase of the ENSO, NAO, AMM, and AWP. As discussed in Section 3.1.1, the large numbers of TCs were formed during the neutral conditions of ENSO and NAO, larger AWP, and positive AMM. According to Krishnamurthy et al. [76], TCs exhibit a quasilinear response in the tropical North Atlantic. Thus, stronger El Niño events inhibit the genesis of TCs due to the increase in the number of days with strong vertical wind shear. However, the negative and positive phases of ENSO show a similar number of TCs affecting Cuba.



Figure 13. Percentages of TCs generated during negative, neutral, and positive phases of ENSO, NAO, AMM, and during smaller, normal, and larger AWP (filled blue, grey and red bars, respectively); and percentage TC rainfall contributions under each phase of ENSO, NAO, AMM, and AWP, shown by blue, grey, and red hollow bars. Period 1980–2016.

The TCs' rainfall contribution was also computed considering composites of the systems under the same phase of each mode of climate variability and the AWP extremes. The results are shown by the hollow bars in Figure 13.

Regardless of the neutral phase of each mode, the contributions expressed as percentages of the total for the cyclonic season appear to be directly determined by the number of systems. For the NAO, if neutral conditions are ignored, the major number of TCs that affected Cuba were formed during the negative phase, and similarly, the highest percentage (>20%) was obtained during this phase. However, we did not find any significant difference between the mean rainfall contribution during positive and negative NAO conditions (see Section 3.1.1).

Finally, despite there is a great difference between the number of TCs that were formed and affected Cuba during a larger AWP with respect to smaller AWPs, the percentage of the rainfall contribution only differs about 7%, and the difference between the mean TC rainfall of both phases is not statistically significant at the 95% confidence level. According to Wang et al. [54], from August to October, large AWPs are associated with increased rainfall over the Caribbean. Hence, our result may be due to the distance at which the TCs formed during larger and smaller AWP affected Cuba. The PDF for trajectories of TCs during larger and smaller AWP (Figure 7), shows that under larger AWP Cuba may receive affectations from TCs in transit over the Caribbean Sea and the Bahamas, however, during smaller AWP the major track density is observed over the western Caribbean Sea and the western of Cuba, which should receive strong impacts and rainfall contributions.

4. Conclusions

This research has shown the number of TCs that affected Cuba during the cyclonic season (June–November) from 1980 to 2016, and determined their contribution to the total rainfall over Cuba. In this period, Cuba was directly or indirectly affected by 146 TCs formed in the NATL basin, which represents 25% of the total. On average, during each cyclonic season, the country was affected by approximately four TCs that contributed to the total precipitation. According to our results, the principal types of TC that affect Cuban territory are, in order of effect, Tropical Storms, Tropical Depressions, and Hurricanes. Climatic modes of variability influence the number of TCs that affect Cuba, primarily modulated by the extension of the AWP and the SST gradient in the tropical North Atlantic region, measured by the AMM index. The results show that 53.42% of the total number of TCs that affected Cuba were formed during the larger phases of AWP (which prevailed after 1994). Regarding the AMM, 23.97%, 4.11% and 71.92% of TCs corresponded to the positive, negative and neutral phases, respectively. Both larger AWPs and positive AMM phases are also related to SST changes in the tropical North Atlantic region, and to the active hurricane seasons of 2004, 2005 and 2010 in the North Atlantic Ocean basin. Contrary to what was expected, there were small differences in the percentage of TCs that affected Cuba under the positive or negative phase of ENSO, while, in agreement with previous results, the negative phase of the NAO seems to favour conditions for TC formation and effects.

The spatial contribution of TCs that affected Cuba to the total monthly precipitation revealed a seasonal increase in the study period, showing a monthly range from 0–15% in June, 5–10% in July, 5–25% in August and September, 10–33% in October, and 10–50% in November. In addition, the mean value across the study area was calculated for the six months from June–November, obtaining ~6%, 5%, 15%, 14%, 18% and 28%, respectively, which represents an average value for the season of ~11%, in agreement with previous findings for the remaining Caribbean Islands and the southeastern coast of the USA. It is highlighted that November is the month with least precipitation during the cyclonic season, but also the month when the contribution from the TCs was the highest. A possible explanation of these results is the lower translational speed of TCs that affected Cuba during this month.

Finally, the contributions of TCs to the total monthly rainfall from 1980–2016, is, as expected, positively correlated (~0.74) with the number of TCs that affected the territory each month. Both series show positive trends, with the slope being higher for the TC values. This is, in part, determined by

the extreme peaks in the number of TCs, such as those that occurred in 2005. These peaks also coincide with the maximum anomalies in the area of the AWP, and the negative phase of ENSO, and they are also related to the SST in the tropical North Atlantic region. The positive phase of the AMM was associated with a greater number of TCs geneses that affected Cuba than the negative phase. All these results will gain more force when a comparison is done using precipitation station data in a future study, and will be evaluated using precipitation products from several datasets. Furthermore, it is expected that longer periods of TC activity will be considered to reveal the possible role of global warming. Besides, it is intended to perform the analysis by intensities.

Supplementary Materials: The following is available online at http://www.mdpi.com/2073-4433/11/11/1156/s1. Table S1: Name of TCs that affected Cuba during each month of the cyclonic season in the period 1980–2016.

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