EARTH SCIENCES
RESEARCH JOURNAL

Earth Sci. Res. J. Vol. 21, No. 4(December, 2017): 159 - 167

UNIVERSIDAD NACIONAL DE COLOMBIA

HYDROMETEOROLOGY

Quantifying the statistical distribution of Tropical Cyclone Activity in the historical record of the Dominican Republic

Santo Trinidad Alvarez Ysabel[1], Gustavo Adolfo Agredo Cardona[2], David Felipe Rincon[3]

1 Dr. Sc. Candidate at DEHMA, UPC-BarcelonaTech santo.alvarez.ysabel@gmail.com
2 School of Sustainability and Urbnism, Faculty of Engineering and Architecture, UNAL-Manizales, Colombia
3Civil engineering Department, UNAL-Manizales, Colombia

ABSTRACT

In this study, we re-examined the Official Hurricane Database from the National Hurricane Center (HURDAT-NHC), an agency associated with NOAA, for tropical cyclone activity from 1851 to 2012for the Dominican Republic on the island of Hispaniola in the Caribbean Basin. We performed analyses at two different levels for the island (i.e., all of the storm tracks in the Caribbean Basin near to the study area that made landfall and all of the events that crossed the Dominican Republic from a radius of 300 km from the coastline). This study includes the statistical occurrence of these phenomena during the study period and the climatological analysis of all tropical cyclone tracks (112 total events) by decadal seasonal distribution, fifty-year seasonal distribution and monthly seasonal distribution to show the lowest and highest activities. We performed wavelet analysis on the continuous data over a long time series to determine the important frequencies. This analysis provided a general statistical conclusion resulting from the data collected. A landfall probability for the study area corresponding to the long time series of (it's 162) years within a radius of ~100, ~185 and ~300 km, based on the historical climatology tropical cyclone tracks, reveals the likelihood of a strike for a major or a minor hurricane. We present a review of the tropical cyclone activities that passed the Dominican Republic, which also forms part of the author's dissertation.

Keywords: Tropical Storms, Statistical Analysis of TCs, Dominican Republic Hurricanes, Caribbean Sea Hurricanes.

Cuantificación de la distribución estadística de la Actividad de Ciclones Tropicales según el registro histórico para la República Dominicana

RESUMEN

Para el presente estudio se ha tomado la Base de Datos Oficial para Huracanes del Centro Nacional de Huracanes (HURDAT-NHC), dependencia de la NOAA, correspondiente al período de 1851-2012 relativos a ciclónicas tropicales para la República Dominicana (Isla Hispaniola) en la Cuenca del Caribe. El análisis ha sido realizado de dos formas diferentes considerando la geografía de la isla (todos los puntos de posicionamiento de los eventos en la Cuenca del Caribe que han impactado el área de estudio al tocar tierra –impactado-- y todos los eventos que han atravesado la República Dominicana en un radio de ~300 km. Se presenta un estudio estadístico de la ocurrencia de estos fenómenos durante el citado período, incluyendo un análisis climatológico de todos los ciclones tropicales que se han registrado (112 eventos en total) en distribuciones decanales, cincuentenarios y mensuales, indicando la de menor y mayor actividad. Por igual se ha ejecutado un análisis de ondeletas sobre los datos continuos de la serie de tiempo para determinar importantes frecuencias. Finalmente mostramos una probabilidad de ocurrencia de que uno de estos fenómenos toque tierra basado en una serie de 162 años para el área de estudio, dentro de un radio de ~100, ~185 y ~300 km, teniendo en cuenta la climatología de huracanes la cual revela la probabilidad de ser impactado tanto por un evento de menor o mayor categoría. El autor muestra una perspectiva de la actividad ciclónica para el área de la República Dominicana la cual forma parte de su tesis doctoral.

Palabras clave: Tormentas tropicales, Análisis estadístico de los CTs, Huracanes en República Dominicana, Huracanes en el Mar Caribe.

Record
Manuscript received: 22/03/2017
Accepted for publication: 25/08/2017

How to cite item
Alvarez Ysabel, S.T., Agredo CardonaG.A. &Rincon, D.F. (2017).Quantifying the statistical distribution of Tropical Cyclone Activity in the historical record of the Dominican Republic. *Earth Sciences Research Journal, 21(4)*. 159 - 167
doi:http://dx.doi.org/10.15446/esrj.v21n4.63425

ISSN 1794-6190 e-ISSN 2339-3459

http://dx.doi.org/10.15446/esrj.v21n4.63425

1. Introduction

Tropical cyclones are alsoknown as hurricanes or typhoons and are among the most deadlynatural disastersonthe Earth. The Caribbean countries are highlyvulnerable to these natural hazards. The latent vulnerability of the area exacerbates the impact of these hazards, which become natural disasters inthis geographic region andaffect the economic, social and environmental conditions. The North East Atlantic (NEA) and the Caribbean Sea Basin (CSB) are characterized as a high probability zone for the formation, development and impact of tropical cyclones (TC), according to the National Ocean and Atmospheric Administration (NOAA). Millions of people are affected, and economic losses ofbillions of US dollarsare estimatedto occur in the Caribbean regionover the past 30 years. Certain island states in the region are susceptible to earthquakes (3% of the population), but they are more susceptible totropical cyclones (70% of the population) and floods (27% of the population) (NHC-NOAA, 2012; CEPAL, 2010; Gutierrez, M.E. &Espinosa, T., 2010; PNUD, 2008; UNU-WIDER, Report Paper 2008/61).

The hurricane activity in the Atlantic increased over the last decade of the XX and beginning of this century (XXI) and had significant consequences, such as heavy rain and theassociated flooding, deaths, damage and destruction ofcoastal and inland areas throughout the North Atlantic Basin (NAB). The CSB territories are well known as a tropical cyclone pathway because ofthe surrounding environmental flows associated with the location of the islands. This basin has experienced above normal TC activity, ranging from Tropical Depressions (TD) to Major Hurricanes (MH) of Category-3 to Category-5 (H3-H5) on the Saffir-Simpson Scale, as shownin table III (Karmalkar A. V. et al., 2013; IPCC, 2007 and 2012; Steve Graham and HolliRiebeek, 2006; Pielke et al., 2005). These phenomena are the most lethal and costly natural disasters in the area.

Major events have occurred in the tropical cyclonecorridor(San Zenón (1930), David (1979), Georges (1998), Jeanne (2004), Noel and Olga (2007), Emily and Irene (2011)) are among the hydro-meteorological events that have impacted the Dominican territory and producedconsequences detrimental toall areas of society, which isevidence of the urgent need to assess their effects not only by the magnitude of thewinds but alsoby extreme precipitation, which can be properlyconfirmed by the recordings in theGRID-UNEP Database (OFDA/CRED, 2012; Campusano, M., 2009; Cocco Q., A., 2009; PNUD, 2007 and 2008; CEPAL, 2008;PNUD, 2007; UNEP-GRID, 2003).

A TC is a storm system (an atmospheric disturbance) that is characterized by a low-pressure center and numerous thunderstorms that produce strong winds and heavy rainfall. TCoriginates over tropical oceans and isdriven principally by heat transfer from the ocean. Approximately 80 tropical cyclones develop globally each year over the ocean atsea surface temperatures(SST ≥26ºC) and very oftenmovefrom these regions into higher latitudes (equator-ward of 5º latitude North Atlantic Basin [NAB]). Once they are developed andorganized, the storms tend to translatewestward and slightly pole-ward.The commonly used categorized scale referred to in this articleis given in the appendix. The frequency and intensity of hurricanes and tropical storms vary significantly from one year to the next (Graham and HolliRiebeek, 2006; Emanuel, K.2003).

Hurricane climatological analysis can provide a useful tool forstudying the potential damage along the coast or landmass of a country, particularlyin populated areas. Damage tends to increase in future years or along river valley floodplains,ifthe heavy rainfall associated with a cyclone passes over at least one of the five principal mountains ranges in the area and is intensified by these orographic systems (Gutierrez, M.E. & Espinosa, T., 2010; Ministry of Environment, 2010). Hurricane Georges in 1998 and the tropical storms Noel and Olga in2007hadpeakextreme heavy rains of ≥ 500, 330 and316 mm/day, respectively, which accumulated in some mountainous areas of the Dominican territories andcaused more than 457 deaths (ONAMET, 1998; 2007; TRMM, 1998; 2007; EM-DAT: OFDA/CRED, 2012).

We used an empirical study method to investigate the statisticalclimatology of TCactivityin the Dominican Republic (DR) territories.The TCsconsidered for this study were bothmajor (H5with awind speed >241 km/h) hurricanes and minor (≤ 63 km/h) tropical storms or depressions (TS/TD) that made landfall or approachedwithin ~300 km of the study radius. A short overview of the study area is given to provide a better understanding. The article isorganized as follows:(a) the data and methodological method are presented and are followed by (b) the results and discussion derived from this work and(c) the conclusions.

2. Study Area

The study area is the Dominican Republic (DR), a country on Hispaniola Island, which is shared with theRepublic of Haiti and is both a member ofthe so-called GreaterAntilles Islands andpart of the Tropical Cyclone Caribbean Basin, whichforms the NAB when the Gulf of Mexico is included. The Dominican Republic is located between 17º 36´14 and19º 55´57 north latitude and 68º 19´24 and72º 00´33 west longitude.The country is located on the edge of the tropical zone of the Northern Hemisphere and is bordered on the north by the Atlantic Ocean, on the south bythe Caribbean Sea,on the east by theMona Passage and on the west by the Republic of Haiti (Fig. 1). The surface area is 48,670.82 square kilometers, with acoastline of1,228 kilometers(CIA-The World Factbook, 2012; Ministry of Environment, 2010;FAO, 2000). The Dominican Republic hasa tropical maritime climate with little seasonal temperature and two main rainy seasons presented: the Frontal-Convective Season (November-May) and the Cyclonic Season (June-October). Areas of high precipitation are highly influenced by moisture-laden trade winds over the Atlantic Ocean that reaches the country from the northeast, producing so-called orographic rainfalls. The terrain consists of rugged highland mountains (five main hilly orographic systems) withinterspersed fertile valleys irrigated by natural,well-spread hydrographical canals and rivers (CIA-The World Factbook, 2012; Ministry of Environment, 2010; FAO, 2000).

Figure 1. Map of the study area.

3. Data and Methodology

3.1. The Hurdat2 Historical Record Database

Historical records of hurricanes for the DR started at the beginning of the sixteenth century, shortly after the foundation of Santo Domingo´svillages, which had been moved and reconstructed on the west bank of the OzamaRiver after they weredestroyed by a hurricane in 1502. Several sources of information (e.g., historians, researchers and universities) indicate where storms and hurricanes have hit Hispaniola Island, although they have several omissions due to some events that followed the trajectories ofthe storm masses onthe ocean surface (Cocco Q. A., 2009). However, in the present study, we do not usethehistorical tropical cyclone tracks prior to the 1851 yearly recordsconcerning the pathways or approaches of those events that affectedthe DRterritory. This is the case for NOAA, who supplemented theirdata collection and with other sources (local or regional) to gather better data and information.

Ouranalysis is basedon the most recent official worldwide HURDAT Database, from the National Oceanic and Atmospheric Administration (NOAA´s Coastal Service Center), for the Atlantic tropical cyclone activitybasin, including the North Atlantic Basin, the Gulf of Mexico and the Caribbean Sea. This database has beenreanalyzed as part of the Atlantic Hurricane Database Re-analysis Project, as documented byLansea et al. (2008). This study incorporates the reanalyzed data of the long time series from 1851 to 2012 (HistoricalHurricanes Tracks: http://www.csc.noaa.gov/hurricanes/#) as part of the climatological calculations for the TC activity (updated every year as the "six-hourly best track"(00:00, 06:00, 12:00, 18:00 UTC)once the hurricane period from June to Novemberhas passed andincludes theYear, Month, Day, Hour, Name, latitude, longitude, storm movement speed and direction, wind speed and central pressure, storms by location, name and basin. However, prior to the satellite era (1970), limitations exist for the determination of storm tracks, intensities, and landfall areas (table I, appendix section)

The Best Track Data fromthe Atlantic hurricane database (HURDAT2) can be downloaded in ASCII format using the spreadsheet software contained in the office version of the Microsoft Office suite (MS Excel v.2007).The geographical information system (GIS) version of the Atlantic Tracks file database (available at: http://csc-s-maps-q.csc.noaa.gov/hurricanes/download.jsp) wasused toperform the computational analysis and generatemapsusingthe GIS-ArcMap software from the Environmental Systems Research Institute (ESRI), a tool that hasmanyspatial calculation capabilities (Klotzbach, 2011; Chen, K. et al., 2009; Landsea, 2004, 2007). More information is available in Appendix I.

As revised by Landsea et al. (2007), the Atlantic Hurricane Database (HURDAT)contains estimatesofthe maximum sustained surface wind speed at the conventional altitudeof 10 m elevation. To recompile the historical tracks for all tropical cyclone storms, this analysis considers wind strength speed superior to 37 km/h (TD/DS = tropical depression or depression storm) usingwind speed descriptions based on the Saffir-Simpson Hurricane Scale (table 2 in the appendix section). The chart is color-coded to show theintensity for each tropical cyclone by category based on the Saffir-Simpson scale. The graphs obtained as a result of the statistical analysis show classificationsaccording to the same criteria. The statistical computations from 1851 to 2012 forall tropical cyclones consider the multi-decadal, fifty-year (pentads), monthly and general seasonal distributions and other statistical parameters (e.g., tendency, probability).

This methodology (unless the contrary is indicated) considers aradius of approximately300 km from the landmass (Santo Domingo as a single point) to the open sea (the Atlantic Ocean to the north and the Caribbean Sea to the south), considering the upper radius limit of ~370 km permitted by the interactive webpage. This radius includes the tracks of all cyclones with a major effectscaused by both direct and indirect impacts(e.g., flooding, wind force, storm surge) during the study period for theDRland and coastal-sea territories.It is important to mention thatin some cases, the tropical cyclone tracks wererecorded in adjacent or nearby countries such as Cuba, Haiti, Puerto Rico (PR) and the Turks & Caicos Islands. Thus, the orientation of the track, the movement speed of the event, the degree of upslope, the intensity at landfall or approach and several otherparameters are consideredforthe open sea limits of the territories of these countries,as previously mentioned (Figure 1).

3.2Methodology forLandfall Probability Calculations

We used the method proposed by Philip Klotzbach and William Gray et al. (2009) at Colorado State University (CSU) forthe statistical occurrence analysis toinvestigatethe relationship between the frequency and probability of the events. Statistical analysis wasalso used to determine how often a TC will occur near the study area at radii of ~100, ~185, ~300 kmfrom Santo Domingo as a single pointand the return period in years (T)or the occurrence for 1, 3, 5, 10, 20, 25 and 50 years based on the longer period of TC Tracks in the 161-year DR hurricane climatological datafromHURDAT2(Klotzbach, P. and Gray, W. et al., 2009).These distances are justified because events such as TS have produced effects asharmful and severe as hurricanes (the introduction highlights some of these), for which therainfall, not thewind strength, is responsible.

Philip Klotzbach and William Gray methodology display the probabilities of a tropical cyclone passing within a certain radius. It allows the probability of a TCs passing within a specified distance of an area in any particular year to be calculated. The methodology facilitates the awareness of the chances of the closest tropical cyclone occurrence that passes or impacts in a particular point in the study area. To approximate the future likelihood of storms, a Poisson regression model is used because the analysis of the number of tropical cyclones that made landfall over the last century shows that the landfall frequency closely conformed to this distribution. Further descriptions and details related to this topic arepresented in the appendix (section III).

4. Results and Discussion

The climatological analysis of all of the tropical cyclone tracks involved studying the 112 total landfall or open ocean approach events in the study area. The early historical HURDATrecord has been regularlyrevised (Lansea et al., 2004, 2007). We wanted to address questions such as which parametersdetermine the variation in the number of TCs. Is the variation due to SST and wind shear? If so, does combination of ENSO and NOAdrive it? What is the probability of ahit by a major hurricane?

We must keep in mind that tropical cyclones were not formally named before 1950 and are referred to as "UNNAMED" prior to that date. Nevertheless, it was common to name a storm for an important person inthe region based on any relevance the person had during the time of the storm. For example, inthe early XX century, some storms were called theFather Ruiz hurricane, Lily's cyclone, Saint Ciriaco's hurricane and Saint Zenon's hurricane (Cocco Q., A., 2009). Using the data related to the tropical cyclone tracks for the period of 1851 to 2012, we can subdivide the long time series into i) a decadal distribution, ii) a fifty-yeardistribution and iii) a monthly seasonal distribution. In the same vein, (i) a general summary of all tracked events is presented.

4.1. Multi-decadal distribution

For the first decade in the middle of the 19th century, the occurrence of tropical cyclones was low but the occurrencefor the country was4, which included 2hurricanesof category H1orH2 and 2TS. Three made landfall, but the rest remained in the Atlantic off the northern coast.Tropical cyclone activity was rarer duringthe second decade,from1861 to 1870, when only one storm was recorded. A unique hurricane of category H1 hit the entire island (Hispaniola), moving from east to west along the south coast of the Caribbean Sea. Afterit passed thePR Island, itendedinthe neighborhood of Haiti as a weak tropical storm (TS).

GreaterTC activitywas evidentfrom 1871 to 1880 than during the two preceding decades. The trajectories offive TCbrushedthe island's south coast: 4TS and 1H1. The decade from 1881 to 1890hadmore frequentTCactivity, with 6 events; a minor H2, amajor H3, and 4TSwererecorded.The final decade of the 19th century showeda considerable increase inTC activity in the region, with eleven events impacting the study area, whichwas theperiod with the most events everrecorded in the history of theDR. The events included3minor storms between H2 and H1,2majorH3 events, 3TSand 1TD. Most of the stormtrajectorieswere east to northwest or east to west and had significant impacts overthe territories of PR and Haiti.

The first decade ofthe 20th century from 1901-1910 had similar characteristics to the last because ten events were registered: 4H1,1H3,4TSand 1TD (figure3a). FiveTCsoccurred from 1911 to 1920: 2H1, 1H2 and 2TS. Two of these events made landfall in the country onthe easternedge of the island (figure3-b).

The decade from 1920-1930 was the first time that all TC types were registered in the study area,ranging from an insignificant tropical storm to an H5 major hurricane that made landfall over the DR,an H4, and an H2that nearly made landfall. These events all hadtrajectories from east and to east-northwestonboth coastlines (CBS and NAB).

The trend during 1931-1940 for both coastlineswasquite opposite to the previous decade. A total of sevenminortropical storms (7-TS)and only one hurricane (1-H1)were observed.By the end of the 1941-1950 decade,six events had occurred: three hurricanes (2 H1 and 1H3) and three tropical storms ofall categories (2TS and 1TD). It is important to note that 1950was the first year in which a namewasassigned to astorm, which occurred on August 28 (a weak depression). The NHC began to name each seasonal tropical cyclone in1949.

The decadefrom1951 to 1960 showed seven total events; threewereH1, H2 and H3storms, andthe remaining four included3TS and 1TD. The decade from 1961 to 1970 showed the highestTC activity in both quantity and intensity in the study area. Seven major events were trackedin the historical record;fourwereclassified as major hurricanes, and another as a minor hurricane, with1H5, 2H4, 1H3, 1H1, and there were two minor storms classified as 1TS and 1TD.

Six tropical cyclones occurred during the decade 1971-1980, and one was a major category H5hurricane. The rest were classified as minor stormsof intensity typesTS (3) and TD (2). The most dangerous storm, due to its catastrophic damage all over the DR,was the remarkable hurricane David. David occurred on August31, 1979, which caused that name to be erased from the NHCassignments. This major hurricane reached the maximum intensity on the Saffir-Simpson scale and had an enormous impact in terms of the consciousness of the effects that a TC can have on a country. Thereafter, the government, institutions, agencies and civilians put deep emphasis on warnings, preparedness and protection from the impact of any storms approaching the landmass or surrounding sea area. This event was a hallmark in the Dominican Republic TC historical record.

Little stormactivity was recordedfrom 1981 to 1990, with three events recorded, including one major H3hurricane named Emily thatimpactedthe entireisland, including both theDR and HaitionSeptember 23, 1987. The other two tropical events were1TSand 1TD (figure 4d). Six major events were recordedat the end of the 20thcentury,1H3and 2H1, and three tropical storm events classified as TS (1) and TD (2). The major hurricane Georges occurred onSeptember 22, 1998, andcaused great damage tothe country'seconomyand society, as measured by loss of life (figure 4e).

The first decade of the 21stcentury plus two more years (2001-2012) make this period were very busyfor the DR. Twenty events were well categorized and tracked from Sea Coastal Services (SCS-NOAA´s Database) and were classified as follows: 1H5, 1H4and 5H1 hurricanes, along with13TSevents that were weak storms. This decadehadthe greatestquantity ofnamed and mean events: 1.78, or approximately2 peryear. Although some eventssuch asJeanne, Dean, Tomas or Irene that impacted the countrywere hurricanes,the so-called tropical storms Alpha (2005), Noel and Olga (2007),similar tothe previously mentioned hurricanes David and Georges, shocked and shattered the confidence of society due tothe tremendous and devastating environmental damage caused by the extremely heavy rains that occurredover the mountainsandpoured out over the floodplain valleys.

We developed a general summary to visualize the entirety of theTC tracks recorded from 1851 to 2012. It was sub-dived by decadeand tropical cyclone category, i.e.,major hurricanes (H5-H3), minor hurricanes (H2-H1) and weak storms (TS-TD)to allow better visual comparison and comprehension. Consideringstatistical decades by cyclone classification, the periods of 1871-1880 and 1901-1910 showedhurricane activity of four (4) minor hurricanes (H1). The periods of 1891-1900 and 1961-1970 showedmajorH3 and H4hurricane activities, with two of each category. The decades of1931 to 1940 and 2001 to 2012 had the highest amount of tropical storm events (TS),withseven (7) and thirteen (13) respectively (figure 2a).

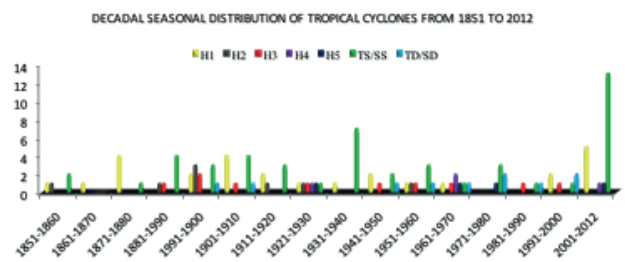

Figure 2. Statistical analysis results for the Decadal seasonal distribution of all TCevents from 1851 to 2012.

4.2. Fifty-year distribution

A seasonal fifty-year distribution wasperformed, and the results obtained from the statistical analysis allowa comparisonoftropical cyclone behavior over162 years of activity. The results infigure 2bshow that the highestfifty-year activity wasthe period from 1901-1950,which had 36 total tropical cyclones with 5 major and 12 minor hurricanes. The fifty-year activitydistribution from 1951 to 2000 showed29 total tropical cyclones anda slight increase inmajor hurricane activity,with8events categorized as H5 (2), H4 (2) and H3 (4). The final period considered wasthe ongoing fifty-year activity distribution of at least twelve years and showed 20 TCtracks,with seven (7) categorized as both major and minor hurricanes.

The TC activity from 1851 to 2012, as summarized by the fifty-year activity distribution,containedall storm types,was characterized bytropical cyclones from H5 to TDand showed that 49 TSwerethe most frequent events affecting the DR territories, followed by 27H1storms for the entire 161-year period for which storm tracks were recorded. When the50-year distributionwas consideredand applied toboth types of events,a considerable numberof recorded tracks (10H1 and17TS)areobtained. For the recent period from 2001 to 2012, ahighernumber of TS (13) was recorded in thisshorttime. Statistics can indicate the overall amount of activity or theprobability that the Dominican Republic territories will be impacted directly or indirectlyby a major or minor hurricane.

4.3. Monthly seasonaldistribution

A distribution of all events in the historical TCsfrom 1851 to 2012 for theeventsduring the 162 years consideredwascalculated on a monthly basis. The hurricane season for this basin runsfrom June to November, and we wantedto determinate which months of the season were more or less active. September wasdetermined to bethe month with the most activity, with 48 total events, followed by August,with 33 events (figure3a).

When the Saffir-Simpsoncategory of the events was consideredby month, September took first place, with 10 major hurricanes (between H5 to H3), 18 minor hurricanes (between H2andH1) and 20weak tropical storms (TS/TD). June hadthe lowestnumber of events,withzero eventsrecorded. July and November hadan equal numberof events(4TS/TD).Rare cases of NAB tropical cyclone activity with tracked events occurred as early as May (2 events) and as late asDecember 3 events(figure 3a).

Figure3bshows the cumulative distribution-dates of the first tropical cyclone formed that passed through the study area. For the study area it shows that for an approximate 300 km radius, the first cyclones (hurricanes) formedprior toJune 15 with a probability of approximately20 to 25 (%)since 1851. For a half year, September shows the peaks with 60% of thehurricanes occurring. (a)he distribution appears to bebi-modal (i.e., with two peaks), especially for tropical storms (TS), withpercentage values of95% and 100% for July and November respectively.

4.4. General distribution

(b)

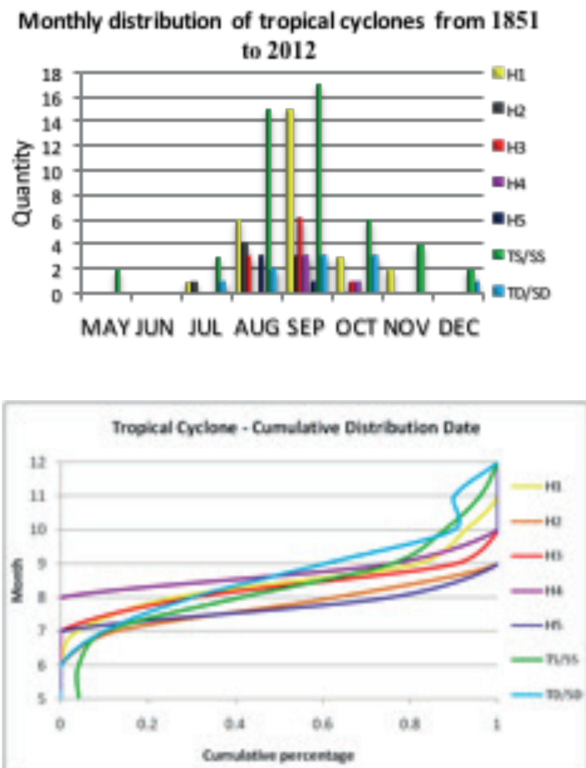

Figure 3. (a) The seasonal monthly distribution chart and (b) CDF from 1851 to 2012.

A general trend can be observed for thedata collected for the period of 1851-2012 in this analysis. The majorityof tropical cyclone events tracked duringthis long time wasTS (49) and H1hurricanes (27) (figure 4a, b). Hurricanes of type H3ledall major types of hurricanes, with 10 total events. The trajectories were in all directions, but moving from east-southeast to west-northwest isthe most frequent direction in this tropical cyclone pathway and could impact any geographical point in the DR territories.

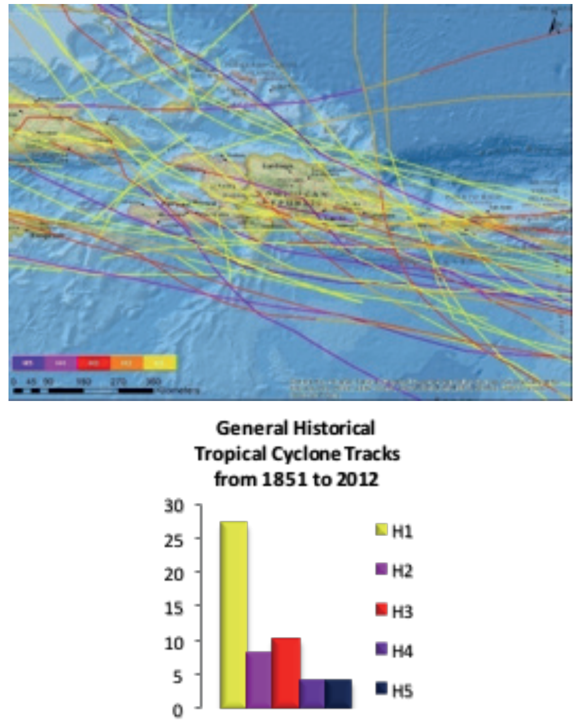

Figure 4. (a) and (b) General historical tropical cyclones events greater than category H1and a statistical analysis of the period, type and area of study.

Based on the climatological historical tropical cyclone tracks recorded from 1851 to 2012 (162 years),we performed a landfall probability analysis for the region in radii of approximately100, 185 and 300 km.The climatology is going to be biased low because of lack of satellite and other technology going back farther in time. It is suggested that the percentages are going to be biased low, because of the under sampling with time. After fixing the measured radii and the total quantity of events tracked for each distance, the previously mentioned CSU methodology wasappliedto analyzethe computational statistical data results. The probability values for 1 or more named storms tracking for ~100-, ~185-, and ~300-kmradiiand their associatedoccurrence yearsare shown in table1.

Table1. Storm landfall probabilities based on 1851-2012 TCclimatology for DR (162 years) based on the CSU methodology (2009).

	Total NS	Total H	Total MH	Total NS	Total H	Total MH	Total NS	Total H	Total MH
	100 km 52	100 km 46	100 km 6	185 km 97	185 km 83	185 km 14	300 km 112	300 km 94	300 km 18
Country	Probability of 1 or More	Probability of 1 or More	Probability of 1 or More	Probability of 1 or More	Probability of 1 or More	Probability of 1 or More	Probability of 1 or More	Probability of 1 or More	Probability of 1 or More
DOMINICAN REPUBLIC	Named Storms Tracking	Hurricanes Tracking	Major Hurricanes Tracking	Named Storms Tracking	Hurricanes Tracking	Major Hurricanes Tracking	Named Storms Tracking	Hurricanes Tracking	Major Hurricanes Tracking
	Within100 km	Within100 km	Within 100 km	Within185 km	Within185 km	Within185 km	Within300 km	Within300 km	Within300 km
	28%	25%	4%	45%	40%	8%	50%	44%	11%

Years Probabilities

	1 or More	MH Tracking	Within100 km				
Year	50	25	20	10	5	3	1
Probability	84%	61%	53%	31%	24%	11%	4%
	1 or More	MH Tracking	Within185 km				
Year	50	25	20	10	5	3	1
Probability	99%	89%	82%	58%	35%	23%	8%
	1 or More	MH Tracking	Within300 km				
Year	50	25	20	10	5	3	1
Probability	100%	94%	89%	67%	43%	28%	11%

A graph of these results was plotted (figure 5),andthe corresponding equationfor the trendline was calculated. We can infer thatastrongand statistically significant correlation exists betweenthe number of storms (probability) and time (occurrences) in years for both MH within approximately 300 km and 185 km, with a R2 value of approximately0.973. Apotential for more storms exists when tropical cyclones appeardistantfrom the landfall mass or are inland,even in years when the storms are very close, the totalprobability of cyclones can be well below normal.In addition, when cyclones seem far away,at least one or two will pass through the study area during those 20 to 50 years. Only one ortwo stormscanspoil a whole season.

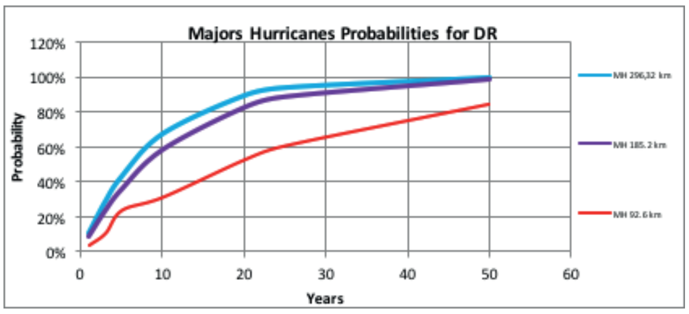

Figure 5. Probabilities of MH occurrences (impact or landfall) directly or indirectly in the DR territories based on the time series from 1851 to 2012.

The historical series generated a TC record of 162 years in length and the basic statistics and variability were evaluatedfor a total of 112 TCs over the region, witha mean of 0.7 events/yearand a standard deviation of 0.9.The relative 95% confidence interval for the mean is (0.9, 1.4).No landfalls within the radius considered from inner mass of the country were observed in 86 (53%) of the 162 years analized, whereasfour TCs madelandfall in76 years (47%) of the analyzed period. A basic spectral analysis of the time series resultedinthe wavelet power spectrum shown in figure 6 (a,b). This wavelet analysis indicates that throughout the time series,the power associated with these phenomena had a 2- to 4-year period.However,most strinkingly,a large peak in power with aperiod between 8 and 16 yearswas evident,whichbegandeveloping towards the beginning of the 20th century.

This analysis will give an opportunity to confirm the above conclusions from the literature examining the CSB and NAB becauseit has beendemonstrated that the SST anomalies in this region havesignificant globalimpacts on the climate (Klotzbach, 2011; cited from Barnston et al. 1997), thus addressing the variability in climatological TCsinthe study area. First, the TCsthat form in the study area haveat least impacted an area in this basin. Second, the seasonal shift in the areas in which theTCsdevelop is quite distinct by month: at the beginning of the season (June and July), development is restricted to the western Caribbean because the SSTs are still cool; later, by August and September, the development shifts eastward to the central and eastern Atlantic as the SSTs become warmer and the vertical wind shear over the basin decreases.Finally, development returns to the western part of the basin during October and November.

The third aspect is the origin of the disturbances thatbecomeTCs. A large portion of TCs form from easterly waves, which are atmospherictroughs spawned over the African continent underunique set of circumstances. Development in the region frequently occurs at latitude of 20º N, which is the only TC basin where this happens. The surrounding variation in the number of TCs is due to the SST and wind shear driven by a combination of ENSO and NOA, which accounts for the nature of the climatological TC variability in the study area (Jury et al., 2011; Klotzbach, P.J., 2011; C. McSweeney et al., 2010; Christopher C. Hennon, 2008).

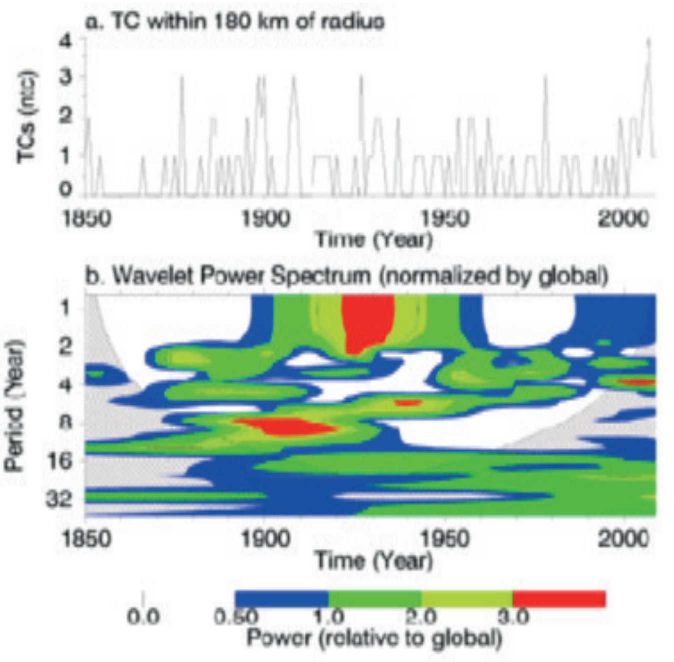

Figure 6. Wavelet power spectrum of the time series of the total number of TCs over the region from 1851 to 2012 with relative 8-year cycles. The cross-hatched region is the cone of influence with a 10% significance level.

5. Conclusion

Based on how close the center of a storm came to the island, the so-called closest point of approach for the study area during the period of 1851-2012 (162-year period) of TCs tracks recorded was calculated. As a result, the following conclusions are presented:

1. The statistical analysis method successfully produced time series of the number of TCs that affected the Dominican Republic territories from the lowest (TD/SD) to the highest (between H3-H5) categories (in the Official Star Hurricane Seasonal TCs yearly activity). Although the DRhas been exposed toTCs prior to the development of SCS/NHC-NOAA Database, the analysis showed thedecadewith the greatestactivity, the fifty-yearperiod with the greatest activity and a time series showing a monthly distribution for these events over the entire161 years.
2. The CSU methodology revealedthe likelihood of an impact for a major or minor hurricane both ata distance and close to the study area. The population in these vulnerable areasmust be aware of and ready for the storms. This topic requires further study.
3. Factor as tropical Atlantic SST, the size of the Atlantic warm pool, and tropical Atlantic SST gradients and low-level trade wind strength, play a critical role in affecting the levels of the NAB and CSB hurricane activity (Jury M.R., 2011; Klotzbach, P.J., 2011; Shieh, O.H. and Colucci, S.J., 2010). On amulti-decadal time scale,due tothe rest of the Atlantic Multi-Decadal Oscillation (AMO) and alterations inboth the size of the Atlantic warm pool and the phase of the meridional mode, the DRoscillation plays a significant role in the Caribbean tropical cyclone activity (Jury M.R., 2011; Klotzbach, P.J., 2011).
4. Quantifying the TC landfall probabilities in the region is important for both seasonal cyclone forecasting and disaster preparedness. Thiswill allow governments, planners and emergency agencies to improve forecasting and preparedness to manage the relative risk for any given event ina TC season in the DR.

Studies by the IPCC (IntergovernmentalPanel for Climate Change) indicated that there is low confidence that any reported long-term (centennial) changes in tropical cyclone characteristics are robust, after accounting for past changes in observing capabilities.The increased Atlantic hurricane activity over the last decade of the 20thand the beginning of this century has hadsignificant consequences, such asa rise in sea level, heavy rain and associated flooding, the loss of human life, damage and destruction to infrastructure and ecosystems, and economic losses both in coastal and inland areas along the whole NAB (IPCC, 2012 and 2007; BID, 2008; CEPAL, 2007; Steve Graham and HolliRiebeek, 2006).Some researchers attribute the recent increase in TC activity to human actions caused by global warming, but others attribute the increased activity to the natural multi-decadal seasonal phenomena that occur in a similar manner to natural earth interaction cycles (geo-physical) activity, neglecting a consideration of the anthropogenicallyinduced rise inglobal ocean surface water temperatures (Karmalkar A. V et al., 2013; IPCC, 2012, 2007; Steve Graham and HolliRiebeek, 2006; Pielke et al., 2005).

The CSB territories are well-known tropical cyclone pathways becauseof the surrounding environmental flows associated with the location of the island of Hispaniola. In general, thisbasin has experienced above normal TC activity from Tropical Depressions (TD) to Category-3 to Category-5Major Hurricanes (MH) (H3-H5) on the Saffir-Simpson Scale. Although the probability of a major hurricane strike is lower within the approximately300 km-h/ fifty-year period (80% - 100%), the probability of minor storms in the category of TS/TD force winds is higher (80% within a decadeand approaching 100% for T = 20, 30, 40 and 50 years).

Although debate tends to concentrate on the reason for the recent increase inTC activity to satisfy both the common people and the scientific community,atrulyinteresting taskremainsafter this statistical analysis of TCsfrom 1851-2012forthe DR.The opportunity for the planned development of the territory is a huge challenge.The environmental heterogeneity and human sustainability must be balancedin terms ofachanging climate and the vulnerability of the Caribbean States (McSweeney, M.N. and G. Lizcano, 2010; UNFCCC, 2007 and 2008; PNUD, 2008; CEPAL, 2007).

Acknowledgment

The authors would like to acknowledge Manuel Gómez Valentín, Sánchez Martí-Juny and Víctor O. Rendón D. for their suggestions. Special thanks also go to the reviewers for the helpful comments that contributed to improve the manuscript.

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APPENDIX

Table II. List of TC categories within 160 nautical miles of the DR extracted fromHURDAT-2-NHC Database

HURDAT PROGRAM: DATA COLLECTION AND COMPILATION http://www.aoml.noaa.gov/hrd/hurdat/hurdat2_1851_2012-jun2013.html

Tropical cyclones affecting the Dominican territories for the mayor period of 1970 to 2012

Order	Name	Intensity	Category	Date	Winds (kph)	Knots
1	S/NOM	Depression	TD/SD	1970/10/07	46	25
2	CARMEN	Tp. Storm	TS/SS	1974/08/30	75	40
3	ELOISE	Tp. Storm	TS/SS	1975/09/17	110	60
4	S/NOM	Depression	TD/SD	1976/10/11	46	25
5	CLAUDETTE	Depression	TD/SD	1979/07/18	46	25
6	DAVID	Hurricane	H5	1979/08/31	280	150
7	FREDERIC	Tp. Storm	TS/SS	1979/09/06	75	40
8	LILI	Depression	TD/SD	1984/12/24	55	30
9	ISABEL	Tp. Storm	TS/SS	1985/10/07	65	35
10	EMILY	Hurricane	H3	1987/09/23	220	105
11	CHRIS	Depression	TD/SD	1988/08/26	55	30
12	CINDY	Tp. Storm	TS/SS	1993/08/16	65	35
13	HORTENSE	Hurricane	H1	1996/09/10	130	70
14	GEORGES	Hurricane	H3	1998/09/22	195	105
15	HELENE	Depression	TD/SD	2000/09/18	55	30
16	DEBBY	Hurricane	H1	2000/08/23	120	65
17	IRIS	Hurricane	H1	2001/10/06	120	65
18	MINDY	Tp. Storm	TS/SS	2003/10/10	75	40
19	ODETTE	Tp. Storm	TS/SS	2003/12/06	85	45
20	BONNIE	Tp. Storm	TS/SS	2004/08/05	46	25
21	JEANNE	Hurricane	H1	2004/09/16	130	70
22	ALPHA	Tp. Storm	TS/SS	2005/10/23	85	45
23	CHRIS	Tp. Storm	TS/SS	2006/08/04	55	30
24	ERNESTO	Tp. Storm	TS/SS	2006/08/27	105	55
25	DEAN	Hurricane	H5	2007/08/18	270	145
26	NOEL	Tp. Storm	TS/SS	2007/10/28	95	50
27	OLGA	Tp. Storm	TS/SS	2007/12/11	95	50
28	FAY	Tp. Storm	TS/SS	2008/08/15	65	35
29	GUSTAV	Hurricane	H1	2008/08/26	140	75
30	HANNA	Tp. Storm	TS/SS	2008/09/02	105	55
31	IKE	Hurricane	H4	2008/09/07	215	115
32	HENRI	Tp. Storm	TS/SS	2009/10/11	40	20
33	TOMAS	Hurricane	H1	2010/11/05	140	75
34	EMILY	Tp. Storm	TS/SS	2011/08/03	85	45
35	IRENE	Hurricane	H1	2011/08/22	140	75
36	ISAAC	Tp. Storm	TS/SS	2012/08/23	105	55

Table III. The chart color codes intensity (category based on Saffir-Simpson scale)

Type	Category	Winds (knots)	Winds (kph)	Line Color
Hurricane	H1	64-82	119-155	Yellow
Hurricane	H2	83-95	155-180	Magenta
Hurricane	H3	96-112	180-202	Red
Hurricane	H4	113-135	202-241	Light Magenta
Hurricane	H5	>135	>241	Blue
Tropical Storm	TS/SS	34-63	63-118	Green
Tropical Depression	TD/SD	<34	<62	Blue Light

Satellite Data Era

Appendix I.

The Central America-Caribbean Landfall Probability Calculations

Methodology

A methodology to display the probabilities of a tropical cyclone passing within a radius of approximately 100 and 185 kmfromvarious islands and landmasses in Central America and the Caribbean was developedat Colorado State University (CSU) and other institutions by the respective main and secondary authors.It allows the probability of a TCs passing within a specified distance of anarea in any particular year to be calculated. This method has been modified and adapted for the specificstudy area in this paper for distance (kilometers), the probability of landfall (T= 1, 3, 5, 10, 15, 20, 25 and 50years) occurrence and for an extended major period of time series for the years that the TCwere tracked(1851 to 2012). The data were taken from NHC-NOAA webpage and the HURDAT2 Database, exported into the Microsoft Excel format and recalculated.

The methodology facilitates the awareness of the chances of the closest tropical cyclone occurrence that passesor impactsin a particular point inthis area. *Figure 4a* displays the tracks of all storms named thatpassed within anapproximate300-km radius,and*appendix Idisplays* the maximum intensity of each storm by distance for the DRfrom 1851 to 2012 but usesthe same criteria for the other distancesconsidered in this paper (~185 km).

To approximate the future likelihood of storms, a Poisson regression model was used becausethe analysis of the number of tropical cyclones that made landfall over the last century shows that the landfall frequency closely conformedto a Poisson distribution, the formula for which is

$$EP = (e^{-p})\ (p^{x})\ /\ x! \qquad (1)$$

where EP = Expected Probability

p = Annual average number of TCsoccurred in the past 161 years

x = Number of storms expected in the upcoming year based on the Poisson formula

x! = Factorial

e = 2.71828

For the probabilitycalculation,the fifty-year (50) probabilities of a major hurricane(MH) tracking within each km of distance fromthe country territories (inland or open-sea mass) wasprovided because most buildings were erected to last at least 50 years and because the construction criteria forthe cost of hurricane-protecting building materials should be based on alonger period. Nevertheless, a descending and minor probability wasappliedtoobtain abetter viewpoint regarding this matter. For further information, see the citations or visit the website http://www.e-transit.org/hurricane/welcome.html