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Spatial and temporal variability of tropical storm and hurricane strikes in the Bahamas, and the Greater and Lesser Antilles

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SPATIAL AND TEMPORAL VARIABILITY OF TROPICAL STORM AND HURRICANE STRIKES IN THE BAHAMAS, AND THE GREATER AND LESSER ANTILLES

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

The Department of Geography and Anthropology

by
Alexa Jo Andrews
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Abstract

Coastal cities throughout the Caribbean Sea are evaluated to determine the geographical distributions of landfalling tropical storms and hurricanes. A strike model is used to measure tropical storm and hurricane force winds. Twenty-six specific locations in the Caribbean are studied over a time period of over one hundred years from 1901 until 2006. The Caribbean Sea geographically covers a small area of the world; however, this analysis demonstrates the wide variability of the frequency of tropical storms and hurricane strikes in this region.

The southernmost portions of the Caribbean, for example Oranjestad, Aruba and Willemstad, Curacao, generally experience lower frequencies of strikes with a major hurricane return period of over 100 years in Oranjestad and Willemstad. Futhermore, Willemstad never experienced a major hurricane strike in the time period. Analyses of the northern parts of the Caribbean including Nassau, Bahamas, Nueva Gerona, Cuba, and Jamaica are locations that experience numerous instances of tropical storm and hurricane landfalls.

Temporal variability is apparent and fluctuates greatly in different regions of the Caribbean Sea. Locations that experience higher frequencies of tropical storm strikes tend to have return periods of two to five years. Other areas with less frequent landfalls have return periods of up to fifteen years. For severe hurricanes, the range is from ten year return periods at Nassau, Bahamas to over 100 years at sites to the south in the study region.

Specific events of landfalling tropical storms and hurricanes, or lack there of, are directly related to La Niña and El Niño events. The 1933 active hurricane season coincides with a significantly strong La Niña event. Less active hurricane seasons often take place during stronger El Niño years.

Chapter 1: Introduction and Literature Review

1.1 Introduction

Tropical cyclone and hurricane strike frequencies have been studied for numerous years with many different objectives. Most importantly, studying past strikes of tropical storms and hurricanes can provide insight on the future frequency of these storms (Jagger et al. 2001). Past research focused on areas such as the United States (Keim et al. 2004), including Hawaii (Chu and Wang 1998); however, little can be found regarding the islands of the Caribbean Sea. All locations affected by tropical storms and hurricanes are important to research; yet, areas such as the United States and the Caribbean seem especially vulnerable with increasing population, tourism, and coastal development (Lyons 2004). Although the islands of the Caribbean are considerably smaller than countries such as the United States, it is important not to disregard this area for many reasons, including hazard mitigation and emergency planning (Jagger et al. 2001).

The Caribbean region can be defined as the area encompassing three main island chains: the Eastern tip of the Yucatán Peninsula in Mexico, the southeastern portion of Florida, the Bahamas, the Greater Antilles, the Lesser Antilles, including the Leeward and Windward Islands, and finally the Netherlands Antilles (http://uk.encarta.msn.com). Islands throughout the Caribbean region repeatedly experience tropical cyclone activity every summer and autumn between June and November, when sea surface temperatures are sufficiently high enough to support hurricane formation. Countless storms never affect land; however, the Caribbean Islands are often severely affected by striking storms, especially during the peak months from mid-August through early-October (Smith 1999). Tropical storms and hurricanes begin as tropical waves that form over the Atlantic Ocean, often off the coast of Africa. The waves coming off the coast of Africa initially begin as thunderstorms that eventually become cyclonic in nature (Keim et al. 2004). These systems are steered toward the west/northwest by the easterly trade winds, which could eventually result in a strike on any of the islands located in the Caribbean Region (Kimball and Mulekar 2004).

The islands located in the Caribbean Region generally do not cover large areas of land and are usually many times smaller than the tropical cyclones that pass over them; therefore, high winds, rainfall, and especially storm surge may completely engulf and destroy these locations (Table 1.1). Information in this Table are approximations based on limited data records.

Table 1.1. Geographical distribution of deaths from Atlantic tropical cyclones from 1492 until 1996 (Rappaport and Fernandez-Partagas (1995)).

Location	Fatalities
Greater Antilles	45,000 (29%)
Offshore Losses	35,000 (22%)
Lesser Antilles	35,000 (21%)
United States mainland (Galveston storm: 8,000)	25,000 (16%)
Mexico and Central America	20,000 (12%)
Elsewhere (Azores, Bahamas, Bermuda, Canada, Cape Verde Islands, South America, Ireland)	1,000 (<1%)

A major function in the livelihoods of residents on many of these islands is tourism. Past research on the United States affirms that the country is “vulnerable to tropical cyclones, due to increasing coastal populations, widespread building in the coastal zone, persistent beach erosion, sea level rise, and coastal subsidence” (Lyons 2004, p. 473). Similar to the topics mentioned in this paper, the Caribbean islands may experience costly devastation attributable to the rapid growth of resort communities directly on the coast.

Muller and Stone (2001) studied hurricane and tropical storm return periods for largely populated coastal communities as opposed to evenly distributed points along the

United States East Coast to the Gulf Coast. Results from this research show that the average return period for major hurricanes ranges from twenty to 100 years for points ranging from South Padre Island, Texas to Cape Hatteras, North Carolina. Along with research by Muller and Stone (2001), other studies have been completed on tropical cyclones in the United States. Simpson and Lawrence (1971) conducted research on the United States Gulf Coast and East Coast by segments; Elsner and Kara (1999) researched counties along the United States East Coasts. Hurricane return period research has been typically focused on segments of the United States, leaving the islands of the Caribbean untouched.

1.2 Objectives

Little research has been conducted in the past on hurricane and tropical storm strikes on Caribbean Islands. This thesis examines the climatology of past strikes of tropical storms and hurricanes in the Caribbean Region over the past 106 years, specifically the largely populated coastal cities on islands including the Bahamas, Jamaica, Cuba, Puerto Rico, the Virgin Islands, and the Windward and Leeward Islands extending to Aruba. Twenty-six islands throughout the Caribbean Region were chosen for this study to determine tropical storm and hurricane return periods. The primary objectives are:

1) To produce a time series of historical tropical storm or hurricane strikes at each particular location chosen in the Caribbean Region and characteristics of the storm at the time of strike (i.e. Category of storm, winds, etc.).
2) To calculate the annual return periods of tropical storms, minor hurricanes, and major hurricanes for each of the locations chosen for the study.
3) To provide possible explanations of the results determined in this study.

1.3 Literature Review

Various studies have been conducted on the frequency of striking hurricanes for areas all over the world; however, the Caribbean Islands have not often been included among these studies. For example, in a study by Smith (1999), East Coast hurricanes were researched to determine frequency and intensity of storms over a series of ninety-nine years and to analyze whether storms are increasing in frequency. Smith's research determined that, after a slow period of hurricane formation in the 1970's, the frequency of hurricanes is increasing again (Smith 1999). Tropical cyclone return periods for Hawaii have been determined to improve disaster preparedness and for future building purposes (Chu and Wang 1998). In this study, hurricane data were gathered from the National Hurricane Center for the years 1949 through 1995. While strong storms are deemed rare in proximity to Hawaii, this study proved that the average annual occurrence rate of hurricanes for the vicinity of Hawaii is about 13.9 years. Results from this study will hopefully be useful in disaster planning concerning mitigation for these areas. A return period of 137 years was calculated for major hurricanes in the vicinity of Hawaii and results also showed return periods ranging from 59 to twelve for weaker-scale hurricanes (Chu and Wang 1998). Hurricane frequency and strike variability in the North Atlantic Basin and the Gulf of Mexico were researched to discover trends in coastal storms (Keim et al. 2004). Results of this study showed some areas that experience recurring strikes as opposed to those that are affected once every so often. The climatology of tropical cyclones originating in the Atlantic was studied to examine the annual cycle of tropical activity (Landsea 1993). This study revealed that damage from hurricane and tropical cyclone activity is steadily increasing along with the population boom in coastal areas of the United States. Keim et al. (2007) produced a study entitled "Return Periods of Tropical Storm and

Hurricane Strikes from Texas to Maine” (Figure 1.1) This thesis is a continuation of the work by Keim et al. regarding tropical storms and hurricanes in the United States.

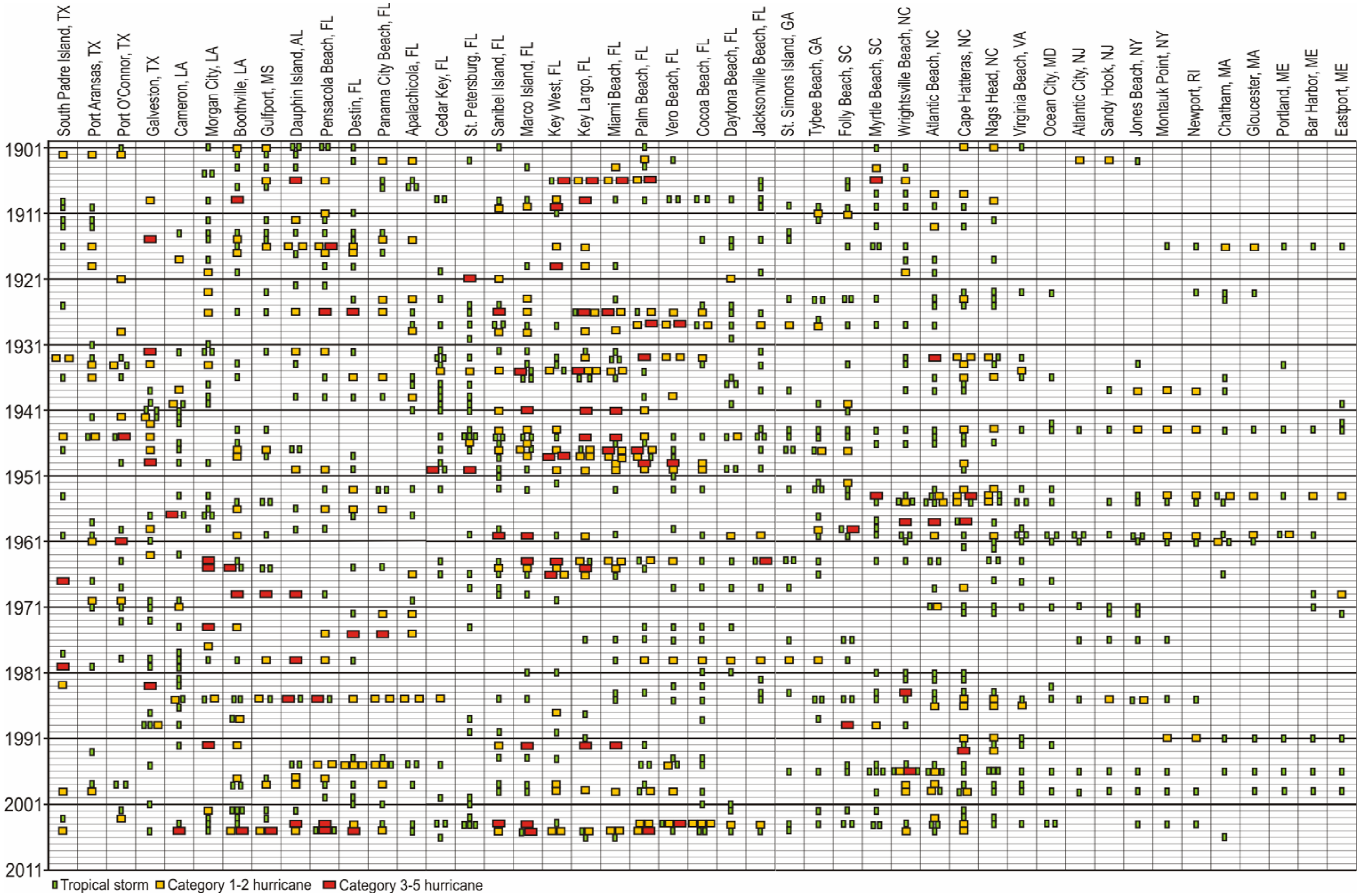


Figure 1.1. Spatiotemporal distribution of tropical storm and hurricane strikes from Texas to Maine. Modified from Keim et al. (2007).

Larson et al. (2005) focused on the climatology and interannual variability of striking tropical cyclones in the United States and Mexico, but only touches on the Caribbean. In this paper, research was conducted on different influences on tropical cyclones, including El Niño and La Niña in which results show that La Niña events usually produced an increase in tropical activity in the Atlantic basin, and with opposite results for El Niño events. Areas in the Caribbean, though, are mentioned in Landsea et al.'s (1999) analysis on Atlantic Basin hurricanes and the effects on the storms from fluctuations in the climate. This research determined that tropical cyclone intensity and frequency are directly impacted by variations in the El Niño-Southern Oscillation for both the United States coast and the Caribbean (Landsea et al. 1999). Additionally, it can be determined in this study and in research conducted by Goldenberg et al. (2001) that the Caribbean Sea generally experiences increased hurricane activity during periods of warmer sea surface temperatures (SST's) as a result of variations in the Atlantic Multi-decadal Oscillation (Goldenberg et al. 2001).

Many factors contribute to the location of the formation and landfall of tropical storms and hurricanes, including El Niño/Southern Oscillation (Pielke, Jr. and Landsea 1999) and the possibility of global climate change (Balling, Jr. and Cerveny 2003). In La Niña conditions, sea surface temperatures are cooler along the coast of South America, which may result in increased tropical cyclone activity within the Atlantic Ocean by creating a favorable upper air environment for storm formation and development (Larson et al. 2005). These conditions, along with heightened activity of tropical cyclones in this area, may have a significant effect on the islands of the Caribbean (Goldenberg et al. 2001). In contrast, El Niño conditions typically result in warm phases off the coast of South America which, in turn, produce an increased amount of vertical wind shear in the Atlantic and Caribbean resulting in fewer tropical storms and hurricanes (Landsea et al. 1999).

The idea of global warming as a contributor to the increased numbers of tropical storm and hurricane development is introduced in many papers researching increases in storm formation. Pielke and Landsea (1998) investigated whether human-induced climate change contributes to enhanced weather-related impacts on society, including hurricanes and tropical storms. This research concluded that an increase in storm-related damage and destruction is most likely a result of societal changes, considering population, building cost increases, and enhanced assets. Pielke at al. (2006) point out that no documented correlation between tropical cyclones' behavior (i.e. rainfall, sea level, and storm surge) and global warming has been established. In contrast, research conducted by Emanuel (2005), examines global hurricane activity and its positive relationship with the increasing global climate. Societal changes resulting in increased destruction from weather events is brought up again in Changnon (2003). In this study, after assessing loss from previous hazardous events the author concludes that changes in society provide enhanced vulnerability to destruction from storms. In opposition, Anthes et al. (2006) state that climate change will in fact impact tropical cyclone characteristics. They conclude that global warming has a direct impact on sea surface temperatures, which will in fact affect tropical storms and hurricanes (Anthes et al. 2006). Webster et al. (2005) examines the idea that hurricanes are directly correlated with consistently increasing sea surface temperatures. Although he determined that discrepancies in hurricane statistics from year to year are too prevalent to conclude a trend is taking place, his conclusion states that an overall increasing trend in hurricane frequency and intensity is inevitable (Webster et al., 2005). Curry et al. (2006), note that past increases in tropical cyclone activity is directly correlated with increases in sea surface temperatures. Also, it is determined that greenhouse warming is increasing the intensity of tropical cyclones (Curry 2006).

Chapter 2: Methods

2.1 Study Area and Hurricane Data

Previous research on annual tropical storm and hurricane return periods have been conducted on the United States, including studies by Muller and Stone (2001) and Keim et al. (2007). Simpson and Lawrence (1971) analyzed the Gulf and East Coasts where hurricane strikes were determined based on equally distributed 50 mile segments of coastal areas. However, points along the United States coast chosen by Muller and Stone (2001, p. 951) are distributed based on "well-known coastal cities, seaports, and beach resorts, and they are not equally spaced along the coastline." The concept of this thesis will be analogous to the methods of Muller and Stone (2001), and Keim et al. (2007) in determining the location of storm strike and the effects of the land in its path.

The Caribbean Islands cover an area of 1,553,016 square kilometers of the Caribbean Sea and are inhabited by over thirty million people, not including millions of tourists that vacation there (KEWL 2006). Locations in the Caribbean Region are extremely popular tourist destinations and are often frequented by people from all over the world, often during hurricane season that falls during summer when traveling is easier.

Twenty-six cities throughout the Caribbean islands were selected for analysis based on proximity to the coast, population, size, and/or popularity regarding tourism as opposed to evenly distributed locations (Figure 2.1). Each of these locations fall at different geographical points and can be organized based on coordinates of latitude and longitude. To determine past strikes of tropical storms and hurricanes for each location, tropical cyclone data were recorded according to each latitude and longitude and coordinate. Two sources of information are used in this research: www.weather.unisys.com/hurricane/atlantic and www.wunderground.com/tropical. These two sites provide archival data dating back to 1851.

From either of these two sources, a map of the tracks of tropical storms and hurricanes can be found along with the coordinates of the paths that the storms followed. Tropical storm and hurricane paths vary throughout hurricane season; however, most tropical cyclones begin as easterly tropical waves in the eastern Atlantic (Kimball and Mulekar 2004). Trade winds blowing in the same direction steer these storms toward the west/west-northwest, in the general direction of the Caribbean Sea. It is possible for storms to form in the Caribbean Region, usually later in the season, as well as the Gulf of Mexico, earlier in the season.

Figure 2.1. Twenty-six locations chosen throughout the Caribbean Region for analysis of hurricane strikes.

2.2 Methods

Tropical storms and hurricanes are both included in this study and all storms can have an extreme range of sizes and intensities (Lodge and McDowell 1991). Major hurricanes have caused severe destruction in the Caribbean in the past, such as Hurricane Charley in

Cuba or Hurricane Ivan in Jamaica and Grand Cayman (Franklin et al. 2006). Less intense tropical storms, though often times smaller in scale than hurricanes, may sometimes cause devastating floods throughout the Caribbean Islands (Franklin et al. 2006). Tropical storms have winds between thirty-eight and seventy-four miles per hour (61 to 119 km per hour) while hurricanes are categorized on the Saffir-Simpson Scale and have sustained winds from seventy-five miles per hour (121 km per hour) to wind speeds of over 155 miles (249 km per hour) per hour. However, these storms can vary immensely in size—the eye of a hurricane is twenty miles (thirty-two km) wide on average, but may be significantly greater in a major category three, four, or five hurricane (Smith 1999). The radius of a tropical cyclone, which also regularly varies, can be defined by the "location and area of threshold wind speed" (Larson et al. 2005, p. 1248). Hurricane Bertha, for example, struck the United States as a category 2 hurricane; however, its radius of winds measured 186 miles (300 km) and the storm caused widespread damage (Kimball and Mulekar 2004). Hurricane Bret, in contrast, was a category 4 hurricane whose wind radius measured only eighty-seven miles (140 km) producing less extreme damage over a less populated area in the southern portion of Texas (Kimball and Mulekar 2004). Variations in magnitude similar to these situations must be taken into consideration when measuring wind speeds of tropical storms and hurricanes at times of strike. Not only may storm size vary, the right-front quadrant of any approaching tropical storm or hurricane characteristically contains the strongest winds and surge; therefore, resulting in winds extending farther to the right of the storm as opposed to the left (Muller and Stone 2001).

To determine tropical storm and hurricane strikes for these cities, a strike model is used as in Muller and Stone (2001) and Keim et al. (2007) (Figure 2.2).

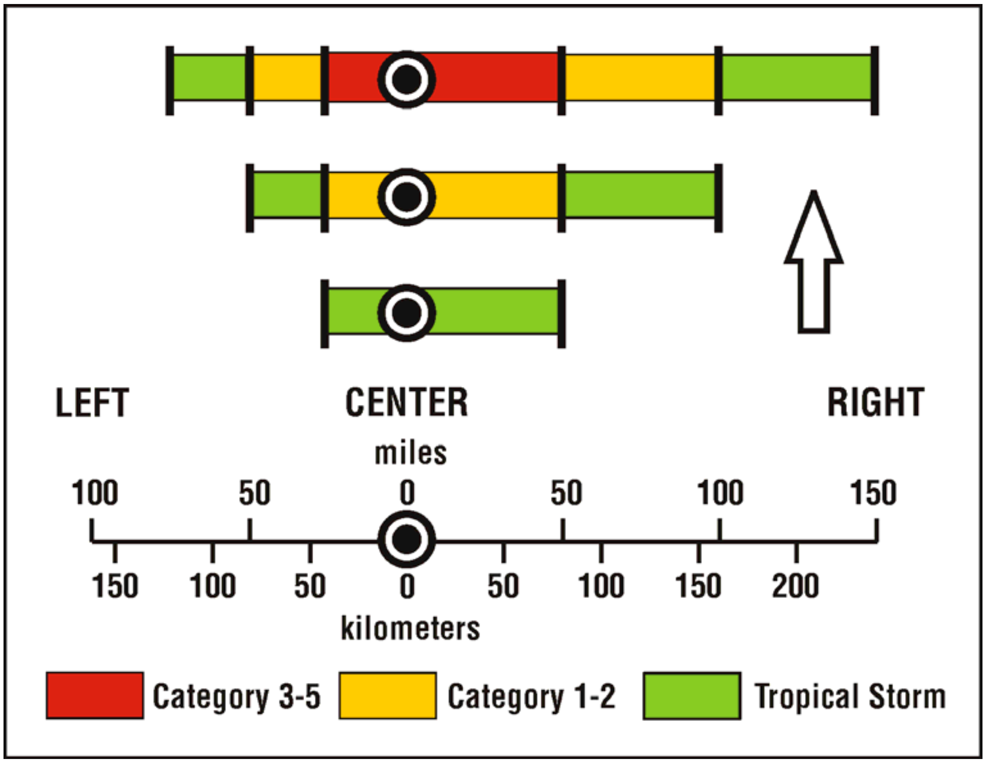


Figure 2.2 Hurricane Strike Model demonstrates the wind swath for major hurricanes (categories 3-5), minor hurricanes (categories 1-2), and tropical storms. The direction of the motion of the storm is displayed in this figure. Source: Muller and Stone (2001).

The strike model is used because the variability in storm sizes is not adequately measured and documented (Keim et al. 2007). As a result, proximity to the storm track plays a role in the type of strike that is recorded for any location. For example, if a category 4 hurricane passes through the Caribbean near Kingston, Jamaica, Negril may only experience category 1 strength winds and surges. The method used by Keim et al. (2007), and by Muller and Stone (2001), is based on the size of a storm from its radius, which may be "defined by the location and area of threshold wind speed" that varies widely and is not necessarily proportional to tropical cyclone intensity and its forward moving direction (Larson et al. 2005, p. 1248). The strongest wind speeds and surges are typically felt in the front, right quadrant of a tropical storm or hurricane (Muller and Stone 2001). Therefore, during a tropical storm, the effects of tropical storm force winds are assumed to be felt 50 miles (80 km) to the right of the center and only 25 miles (40 km) to the left. For example, Georgetown, Bahamas may experience tropical storm force winds; however, Nassau may not experience any winds that reach tropical storm strength. During a minor hurricane, categories one or two, hurricane force winds and surges are assumed to be felt 50 miles (80 km) to the right of the center and 25 miles (forty km) to the left. As well, tropical storm force winds are assumed to be felt an additional 50 miles (80 km) to the right and 25 miles (40 km) to the left. Finally, a major hurricane, categories three, four, or five, may result in category three or higher force winds and surges 50 miles (80 km) to the right of the center and 25 miles (40 km) to the left. Minor hurricane force winds are assumed to be felt an additional 50 miles (80 km) to the right and 25 miles (40 km) to the left, and tropical storm force winds an extra 50 miles (80 km) to the right and 25 (40 km) to the left (Muller and Stone 2001). Based on the assumption that all storms are nearly the same, a measurement of tropical storm and hurricane wind speed size can be accomplished with this model, which was applied to each of the study locations throughout the Caribbean Region for tropical storm and hurricane tracks over the last century or so, from 1901 to 2006.

Using this model, all tropical cyclones were catalogued, from 1901 to 2006 (Appendix A). In Appendix A, the twenty-six locations included in this study are in alphabetical order according to country. During the past 106 years, 236 tropical storms, hurricanes, and major hurricanes struck one or more of the twenty-six Caribbean cities in this study. Of those 236 tropical storms 108 hurricanes struck one or more of these cities; of the 108 hurricanes, forty-five of these storms struck as a major hurricane. Tropical storm and hurricane observation platforms have transformed greatly since the early 1900s (Figure 2.3). While technological advances have taken place in recent years, records should still be significantly accurate for landfalling tropical storms and hurricanes.

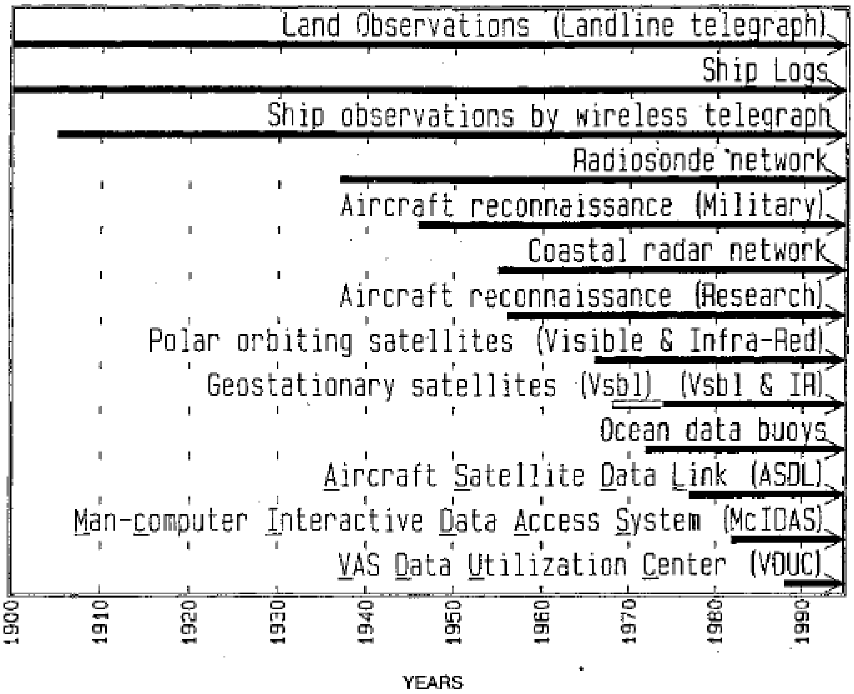


Figure 2.3. Changing technology in tropical storm and hurricane data observation techniques in the Atlantic Basin. Source: Neumann et al. (1993, p. 14).

2.3 Return Period Methodology

A return period can be defined as “the average period in which an event is expected to recur once” (Chu and Wang 1998) and in this case refers to one particular coastal location on an island in the Caribbean Region. Historical tropical storm and hurricane data were collected for each of the twenty-six chosen cities throughout the Caribbean Region, over the past 106 years. Using the Hurricane Strike Model, each storm strike over this period of time was analyzed to determine the strength of winds at a specific location. Based on these conclusions, return periods were calculated for each city chosen in the Caribbean Region according to the number of years in the dataset and the number of strikes for the particular location. Calculations were determined for all strikes including tropical storms, minor hurricanes, and major hurricanes.

Chapter 3: Return Period Analysis

3.1 Temporal Analysis

Because of the consistently warm sea surface temperatures during the months of hurricane season in the Atlantic Ocean and the Caribbean Sea, these waters are typically where the formation of tropical storms and cyclones begin (Landsea et al. 1999). In analyzing the 106 years of storm data, 236 tropical storms and/or hurricanes struck one or more of the twenty-six locations in this study (Figure 3.1).

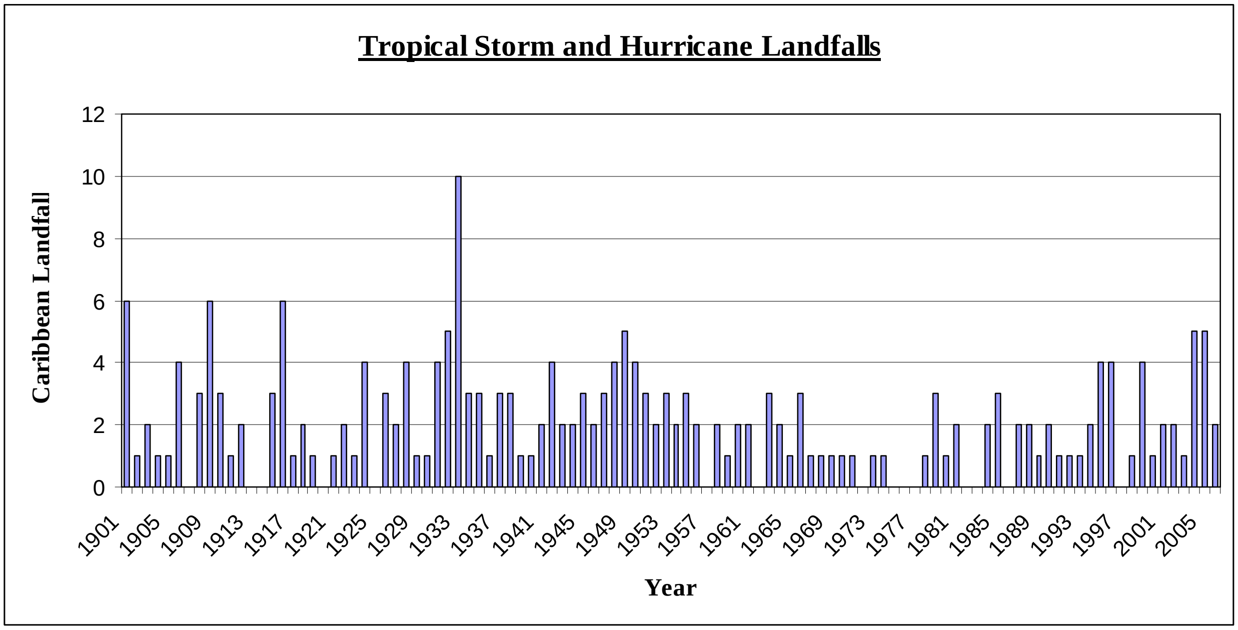


Figure 3.1. Total number of tropical storms/hurricanes striking over 106 years for twenty-six chosen locations in the Caribbean Region.

The waters of the Caribbean Region cover an extensive latitude and longitude range, from 12.1°N to 25°N and 61°W to 82.8°W therefore allowing tropical storms and hurricanes ample time to form and grow into intense storms as shown in the tropical storm and hurricane paths in Appendix B (Kimball and Mulekar 2004). The Caribbean Sea, in conjunction with the North Atlantic ocean, experiences fluctuations in sea surface temperatures on an annual basis. In the annual cycle, sea surface temperatures peak around September 10, on the average, which is close to the mid-point of the hurricane season. However, sea surface temperatures in the North Atlantic Ocean also tend to be warmer or cooler than normal, a multi-decadal cycle referred to as the Atlantic Multidecadal Oscillation (AMO) (Dijkstra et al. 2006). Studies have shown that climate variations in the United States are well correlated with the AMO, resulting in more or less rainfall according to the AMO phases. Not only does the AMO have an effect on rainfall in the United States, but hurricane activity has been proven to increase during positive AMO phases, and conversely, they decrease during negative AMO phases (Dijkstra et al. 2006). Trade winds are generally weaker during negative phases of the AMO, and the opposite during the positive phases (Virmani and Weisberg 2006). In this study, a decrease in tropical cyclone activity is apparent during a negative AMO phase, 1970 through 1994, following higher activity during the years 1950 through 1964. These earlier years can also be associated with a positive period of the AMO. To demonstrate this association, the yearly index of values of the AMO were recorded from data from the Climatic Diagnostics Center (CDC) (www.cdc.noaa.gov/Correlation/amon.us.data) for the years 1948 through 2006. These averages were compared with the number of tropical storm and hurricane strikes in the Caribbean Region (Figure 3.2). Figure 3.2 demonstrates that the possibility of a correlation between data exists when the AMO is compared to the temporal distribution of tropical storm and hurricane strikes. The Spearman Rank Correlations test was conducted and the association between the number of storms in the Caribbean Region and the AMO was highly significant ($r_s = 0.4885$; p. = 0.0001).

It is apparent that many tropical storms and hurricanes wreak havoc by affecting more than one island at a time. In some instances, a tropical cyclone may initially strike as a tropical storm; however, it may re-enter the ocean and strengthen into a hurricane before striking another location.

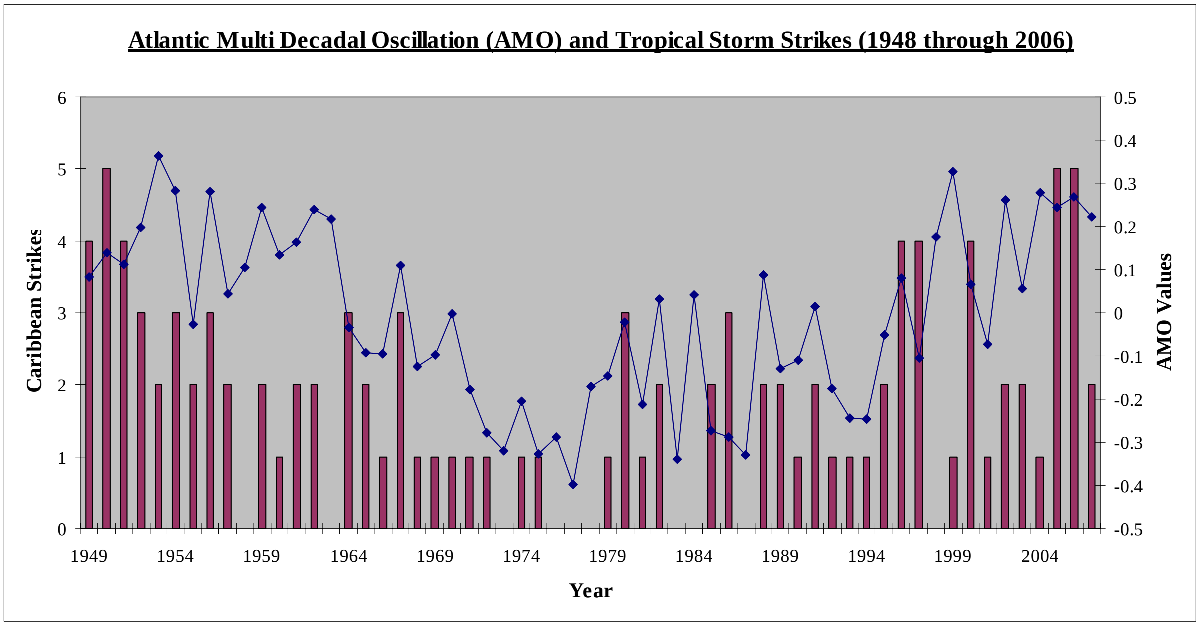


Figure 3.2. Tropical storm and hurricane strikes associated with the Atlantic Multidecadal Oscillation (AMO) sea surface temperature value departures from the normal, from 1949 through 2006 (http://www.cdc.noaa.gov/Correlations /amon.us.data).

In 1915, twelve islands included in this study experienced either a tropical storm or hurricane strike from the Galveston Hurricane, named after its destructive landfall on the United States (Figure 3.3). This storm began its path striking Port-Louis, Guadeloupe and St. John's Antigua as a minor category one storm. The hurricane continued on throughout the Caribbean, weakening to a tropical storm as it struck the Dominican Republic. The Galveston Hurricane again reached the warm Caribbean Sea striking all four Jamaican cities chosen for this study. This hurricane initially struck Kingston as a category one before strengthening to a category two when striking Ocho Rios, Montego Bay, and Negril. This storm continued on its path and further strengthened to a major category three hurricane, striking Nueva Gerona, the southern portion of Cuba. On land the storm quickly diminished to tropical storm strength as it struck the northern portion of Cuba, at La Habana.

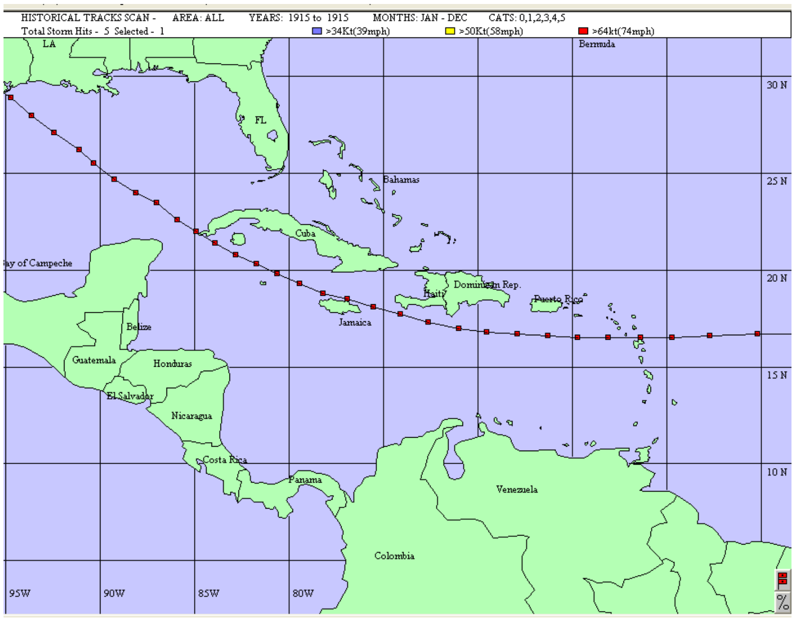


Figure 3.3. Galveston Hurricane track, 1915. Source: Hurrevac Program.

In 1928, the Lake Okeechobee Hurricane affected eleven of the twenty-six Caribbean locations in this study, with seven locations experiencing major hurricane strength winds (Figure 3.4). This storm in particular made its initial strike in the Dominican Republic as a minor category one hurricane and later struck both Charlotte Amalie, St. Thomas and San Juan, Puerto Rico as a category five hurricane. Islands in between these locations experienced strikess of the Lake Okeechobee Hurricane at different intensities.

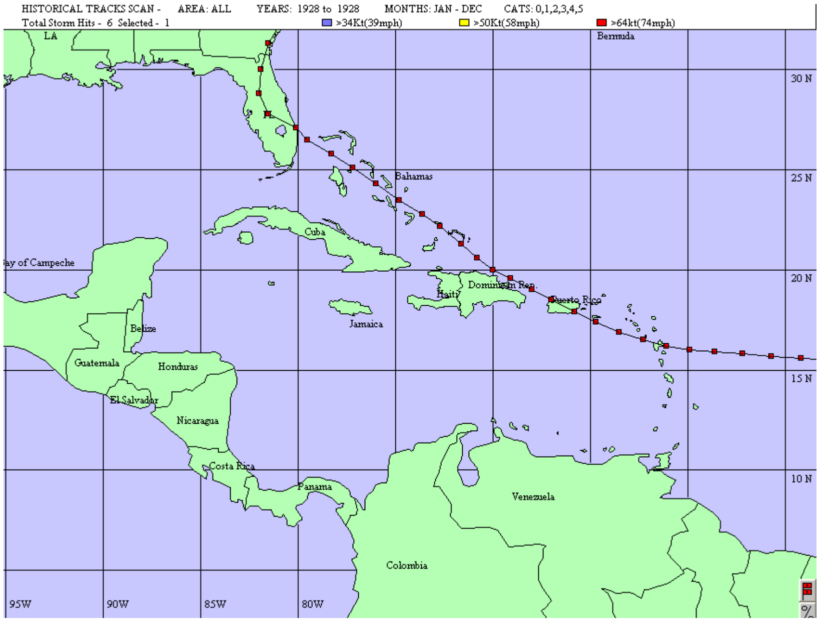


Figure 3.4. Lake Okeechobee Hurricane track, 1928. Source: Hurrevac Program.

Thirteen of the locations in this study experienced a strike from Hurricane David in 1979 whose strength fluctuated from a major hurricane down to a tropical storm (Figure 3.5). The beginning of Hurricane David's destructive path included a strike as a minor category one hurricane on the island of Castries, St. Lucia and continuing in the Lesser Antilles on to Fort-de-France, Martinique, striking as a category two storm. David then strengthened into a major category four hurricane as it struck Roseau, Dominica and gradually weakened as it struck four more islands before Charlotte Amalie, St. Thomas. This storm continued its course of destruction as it struck the Virgin Islands and maintained its strength as a category three hurricane as it struck Puerto Rico. David reached its final peak in strength at a category five as it struck Santo Domingo, Dominican Republic and then weakened significantly as it reached the northern shore of this island and the crossed into the Bahamas, striking Georgetown and Nassau as a tropical storm.

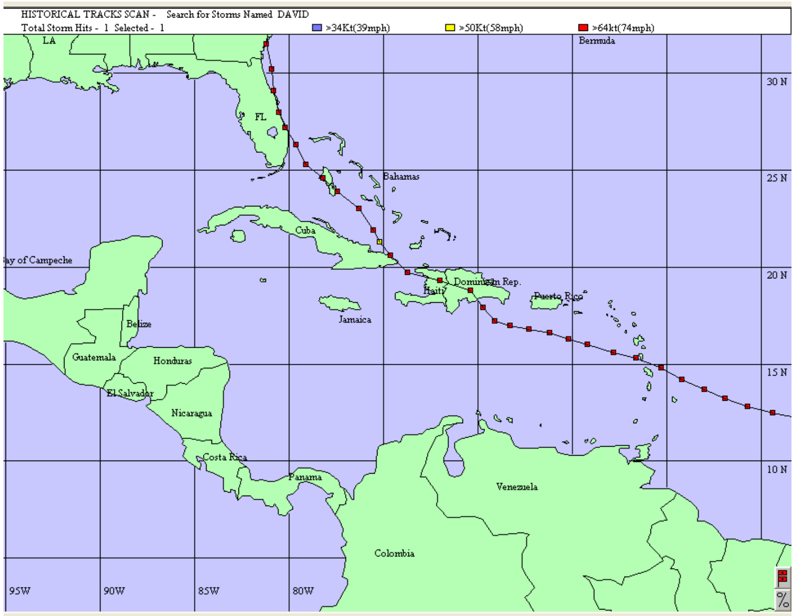


Figure 3.5. Hurricane David track, 1979. Source: Hurrevac Program.

In 2004, Hurricane Ivan struck the United States on the coast of Florida as a major hurricane (Figure 3.6). Before landfall on the Alabama and Florida coasts of the United States, however, the Caribbean Region experienced its devastating power that caused extreme damage in Jamaica and Grand Cayman (Franklin et al. 2006). Hurricane Ivan struck twelve different locations out of the twenty-six Caribbean areas in this study. Unlike many of the other storms that struck the Caribbean islands within this time frame, Ivan initially passed further south than the usual storm path. Ivan struck the island of Grenada as a major hurricane, category three, and remained on a westward path. The storm weakened after landfall, and passed Martinique as a tropical storm before striking Oranjestad, Aruba as a category one storm. As the storm made a northward turn, the warm sea surface temperatures enabled it to strengthen before it made struck Jamaica and Grand Cayman as a major storm, Cuba as a minor hurricane, and onto the United States. The storm moved on, increasing again in strength lasting a record ten total days as a major hurricane (Franklin et al. 2006).

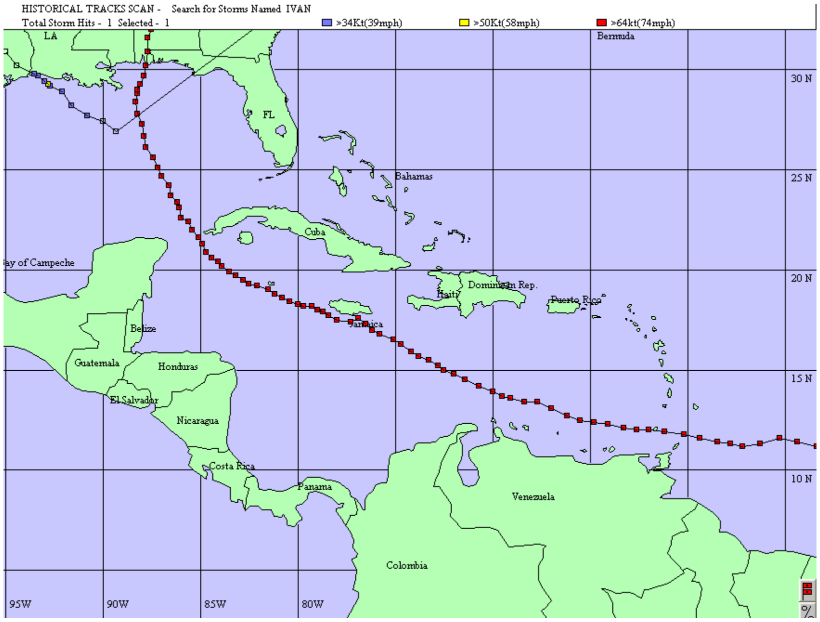


Figure 3.6. Hurricane Ivan track, 2004. Source: Hurrevac Program.

In contrast to the above mentioned multi-striking storms, numerous tropical storms and hurricanes affected only one location in their paths. In 1905, St. George’s, Grenada was struck by Tropical Storm Number One (Figure 3.7). This was the sole island to experience this particular storm. The only affected area in this study by Hurricane Easy in 1950 was

Cuba. Cuba experienced Hurricane Easy as a minor category one hurricane in both La Habana and Nueva Gerona. In 1958, Janice struck as a tropical storm on Nassau, Bahamas and did not affect any other Caribbean islands in this study. Also, in 2001 Hurricane Iris made two strikes on the island of Jamaica only, as a tropical storm in both locations.

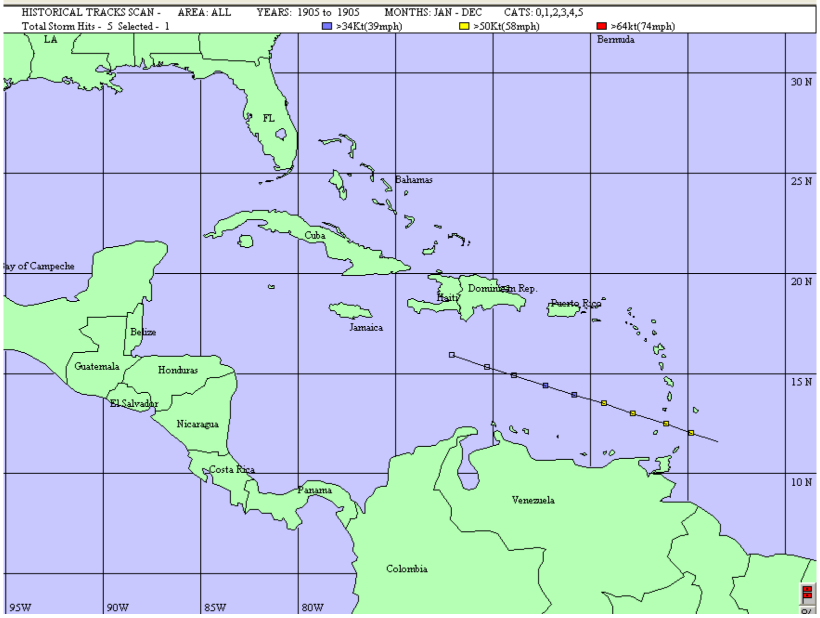


Figure 3.7. Tropical Storm Number One track, 1905. Source: Hurrevac Program.

3.2 Spatiotemporal Analysis of Strikes

From 106 years of historical tropical storm and hurricane data gathered for the twenty-six Caribbean locations chosen for this study, a spatiotemporal time series was produced that merges time, geography, and storm strikes by intensity. It is obvious that the regions throughout the Caribbean chosen for this study experience differing numbers of strikes from tropical storms and/or hurricanes (Figure 3.8).

Tropical storms and hurricanes generally move in a westward and poleward direction; therefore, it is apparent that specific areas are less prone to a strike from a tropical storm (Emanuel 2003). Lower latitudes generally do not experience tropical storms or hurricanes, which is apparent for the cities located in lower latitudes included in this study (i.e. Aruba and

Curacao). Cities located at higher latitudes within the study region experienced much higher numbers of striking tropical storms and hurricanes.

Comparisons in the spatiotemporal aspect of tropical storm and hurricane strikes may be made between Figure 3.8 from this study and the Time Series (Figure 4) from Keim et al. (2007). Both time series analyses display a significant amount of storms during the mid 1920s through the early 1930s. Keim et al. (2007) shows clusters of the storms during this time making landfall mostly on the coast of Florida and around the Gulf Coast. During the same time period, this study shows major clusters around the northern part of the Caribbean Region on islands such as the Bahamas and the northernmost islands of the Lesser Antilles (i.e. Puerto Rico and St. Thomas). One conclusion that could be determined from this comparison is that most storms in the 1920s and 1930s that struck these specific regions of the Caribbean continued on to the southern portion of the United States.

In comparing these two figures, one aspect stands out during the 1940s (Figure 1.1). Keim et al. (2007) also shows these years to be considerably active, while this study's time series shows a lull in tropical storm and hurricane activity. A small cluster can be seen for this time period, with storms again striking around the Bahamas and Cuba; however, this cluster quickly fades as the Caribbean geography extends further southward. Storms during this time period could have possibly passed through the Bahamas or further north before making landfall on Florida's coast, as seen in the study by Keim et al. (2007). In the 1950s, this study's time series figure shows a decrease in strike frequency. The same decrease is apparent in Keim et al.; however, clusters have moved toward the eastern coast of the United States. A significant decrease in striking tropical storms and hurricanes occurs during the 1960s and 1970s in both studies, with activity not significantly increasing until the 1990s, most likely related to negative AMO conditions. This increase is apparent throughout the rest of both studies, through 2006, as the AMO shifted to positive (Keim et al. 2007).

Beginning with the northernmost cities of this study in the Greater Antilles, Nassau and Georgetown, Bahamas, tropical storm and hurricane activity is at its highest. Nassau alone experienced forty-two storm strikes over the past 106 years, while Georgetown experienced thirty-four. Seventeen major hurricanes struck the Bahamas during this time period—ten of which struck Nassau, which is the greatest of all twenty-six locations examined. The majority of these major hurricanes striking Nassau occurred during the 1920s and 1930s.

In Cuba, the cities La Habana, Nueva Gerona, and Santiago de Cuba are examined. All three locations experienced high frequencies of tropical storm and hurricane strikes over the 106 year dataset, with the bulk of storms striking before 1960. The lowest frequencies are found at Santiago de Cuba with twenty-five total storms. Nueva Gerona, the westernmost city examined in Cuba experienced the highest numbers of strikes out of all Caribbean locations, including forty-three total storms along with seven major hurricanes. Hurricane Charley struck La Habana in 2004 as a major category three hurricane as well as Hurricane Number 5 in 1910 and Hurricane Number 10 in 1926.

South of Cuba lies Georgetown, Grand Cayman, a significantly smaller island when compared to Cuba. Georgetown experienced thirty-seven total storms over the 106 year dataset with, surprisingly, only one major hurricane. Hurricane Ivan struck Georgetown, Grand Cayman, in 2004, causing catastrophic damage to the island (Franklin et al. 2006). The remaining tropical storms and hurricanes that struck this island also occurred before 1960.

The four locations included in this study on the island of Jamaica (Kingston, Montego Bay, Negril, and Ocho Rios) experienced an average of twenty-four total storm strikes, mostly

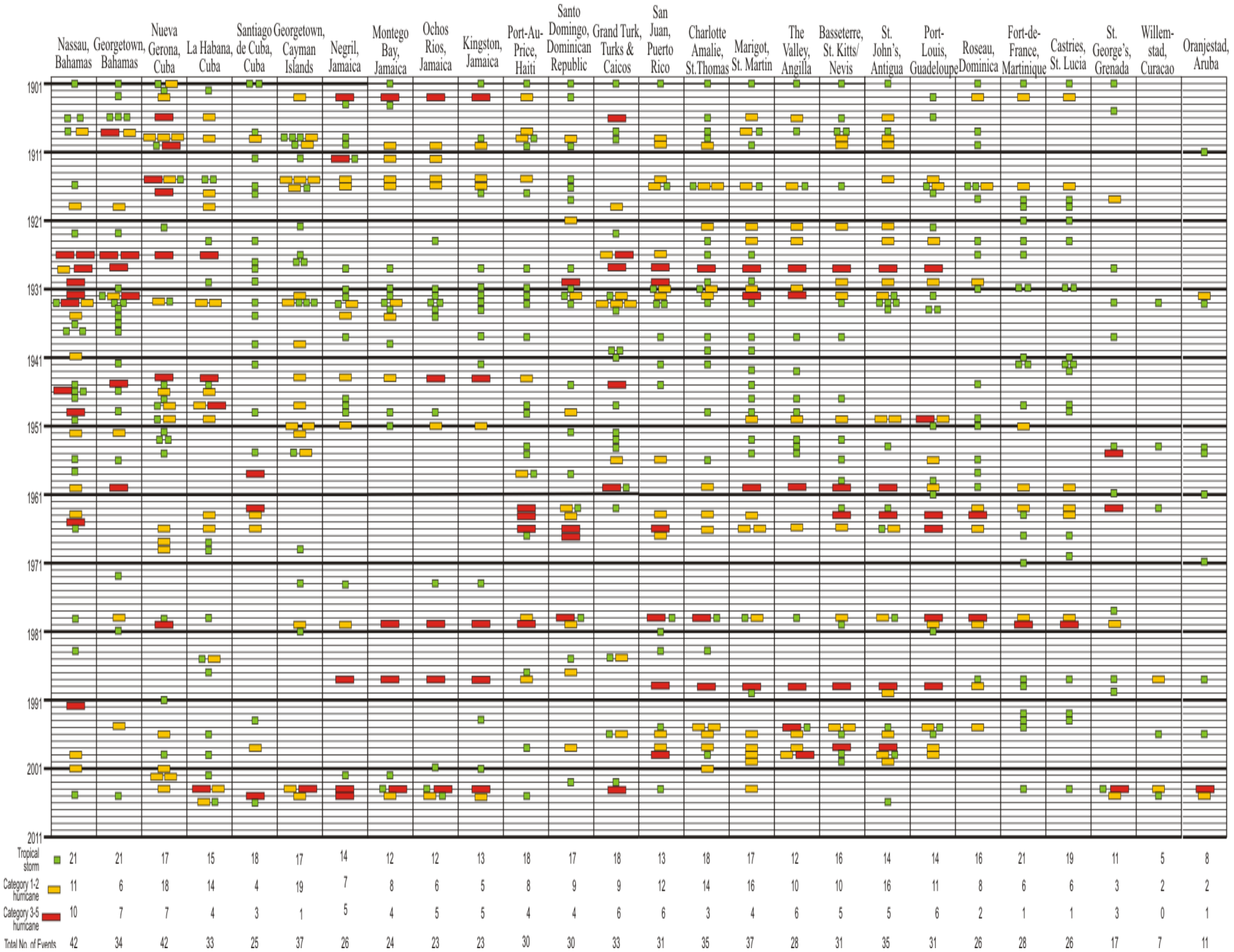


Figure 3.8. Spatiotemporal distribution of all tropical storm and hurricane strikes for twenty-six locations throughout the Caribbean Region.

before 1950 and after 2000. Note that each city on the island may be affected by the same passing hurricane. Further east of Grand Cayman and Cuba is the large island of Hispanola—consisting of Haiti and the Dominican Republic, along with the tiny island of the Turks and Caicos. Port-Au-Prince, Haiti, the westernmost location chosen for this study in this particular location in the Caribbean Region, experienced similar circumstances over the past hundred years as did Cuba, with a total of thirty tropical storm and hurricane strikes on the island. However, an increase in storms is apparent for this location between the years 1950 and 1960. Eighteen of the storms that struck here were tropical storms, while four made struck as major hurricanes. Storm strikes on Santo Domingo, Dominican Republic were also similar to the numbers from Port-Au-Prince; however, a slight increase in total minor hurricane strikes was recorded at this location. Santo Domingo experienced a majority of storm strikes before 1940; however, an increase is apparent in the 1960s. On the tiny island of the Turks and Caicos, Grand Turk experienced thirty-three total storms with six being major hurricanes. Five of the six major hurricanes that struck this location occurred before 1961. The final location within the Greater Antilles is San Juan, Puerto Rico. Results for total tropical storm and hurricane strikes on this island continue the trend of high numbers of total storms with thirty-one overall, including six major hurricanes. Overall, the Greater Antilles experienced a large portion of the tropical storms and hurricanes that formed and/or traveled throughout the Caribbean Sea. All cities within this area each experienced no less than nineteen total tropical storm or hurricane strikes. Many of the total numbers of storms that struck specific islands included strikes from major hurricanes, yet many more included tropical storm strikes.

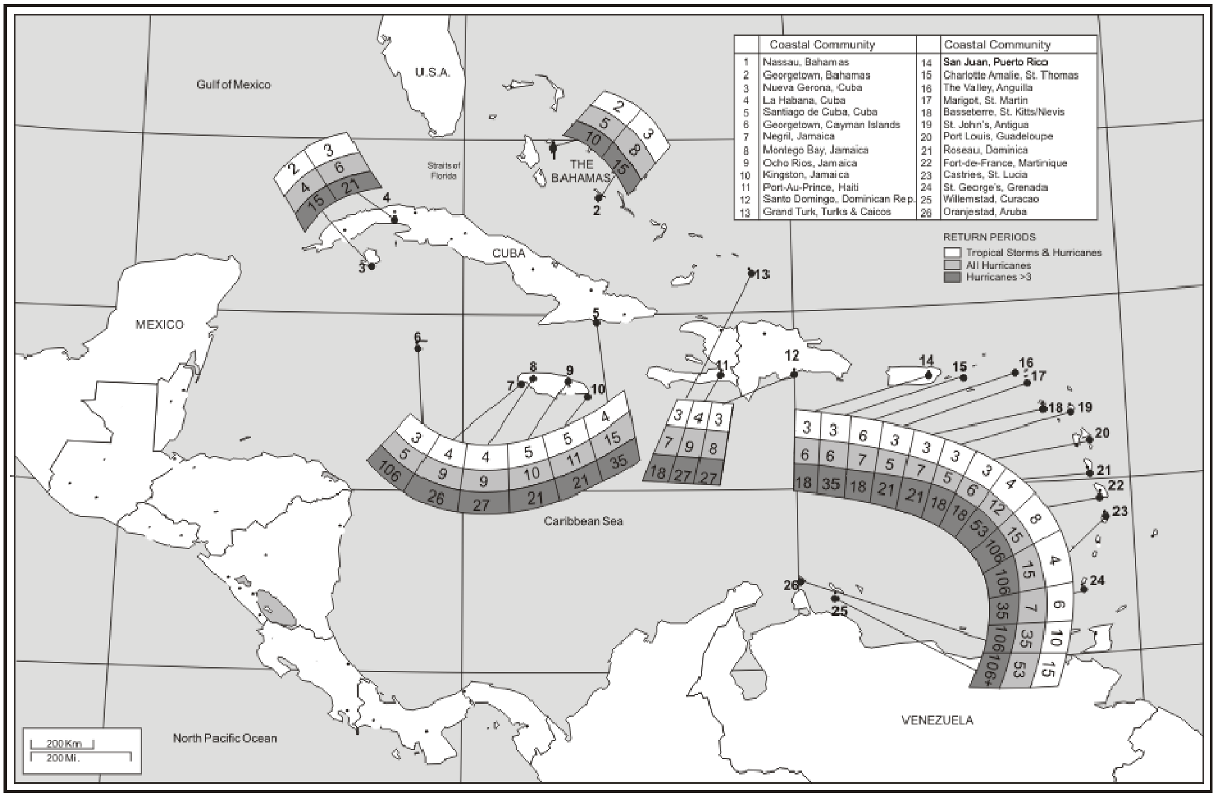
Gradual changes in the distribution of tropical storm and hurricane strikes occurred on the islands making up the Lesser Antilles. The Virgin Islands, which includes some of the most popular tourist locations in the Caribbean Region, make up the northernmost portion of the Lesser Antilles for this particular study. Charlotte Amalie, St. Thomas lies directly east of Puerto Rico and experienced a total of thirty-five total tropical storms and hurricanes over the 106 year dataset. Of these thirty-five storms, eighteen made struck on St. Thomas as tropical storms, fourteen were minor hurricanes, and three made struck as major hurricanes. One of these major storms made struck in 1928 at this location, in the midst of a cluster of striking storms between 1920 and 1933. Eventually named for its landfall on the Florida coast of the United States, the Lake Okeechobee Hurricane struck Charlotte Amalie in 1928 as a severe category five hurricane before moving on to San Juan, Puerto Rico. Further east lies Marigot, St. Martin whose tropical storm and hurricane strike record is the third highest, below Nueva Gerona, Cuba and Nassau, Bahamas. Thirty-eight total storms struck the island of St. Martin during this time period with five of these being major storms. In 1950 Hurricane Donna made struck Marigot as a category three hurricane, followed by Hurricane Hugo in 1989 and Hurricane Lenny in 1999, both striking as category three storms. The Valley, Anguilla and Basseterre, St. Kitts/Nevis experienced somewhat similar results for total striking storms at thirty and thirty-one respectively. While both locations' records include ten minor hurricanes, small differences are apparent with six major hurricanes for Anguilla and five for St. Kitts/Nevis. Tropical storm strikes also differ in this area in that fourteen struck Anguilla and sixteen on St. Kitts/Nevis. In 1995, for example Hurricane Luis struck The Valley as a major category four hurricane; however, weakened as it struck Basseterre as a minor category two storm. Continuing into the Lesser Antilles, St. John's, Antigua and Port Louis, Guadeloupe are both cities that have high records of striking tropical storms and hurricanes; however, gradually decreasing further southward (i.e. St. John's experienced six more total storms than Port Louis, further south in the Lesser Antilles). These five locations, Marigot, The Valley, Basseterre, St. John’s, and Port-Louis, all experienced a significant portion of striking tropical storms between 1920 and 1933, with an increase in the 1990s. Roseau, Dominica experienced a total of twenty-six hurricanes and tropical storm strikes, only two of which were major hurricanes. These two storms struck in 1964 and 1979, respectively. Similarly, Fort-de-France, Martinique had a record of twenty-eight total tropical storm and hurricane strikes with only one being a major hurricane. The sole major hurricane that struck Martinique was category three Hurricane Allen in 1980, while Dominica was affected by both category three Cleo in 1964 and category four David in 1979. Castries, St. Lucia and St. George’s, Grenada are the final islands for this study that are located in the Lesser Antilles. St. Lucia, significantly north of Grenada, experienced a total of twenty-six tropical storm and hurricane strikes. However, Grenada’s record included only seventeen total storms. Although Grenada was affected by a lesser number of storms as compared to St. Lucia, three of the storms were classified as major hurricanes. St. Lucia only experienced one major hurricane, category four Hurricane Allen in 1980.

Two additional islands in the extreme southern portion of the Caribbean Region are also included in this study: Willemstad, Curacao and Oranjestad, Aruba. Located south of most tropical storm and hurricane tracks, both locations experienced the smallest number of total storm strikes with only seven in Curacao and eleven in Aruba. Out of these storms, not one major hurricane struck Willemstad, while only one struck Oranjestad since 1901. Before striking and causing complete destruction in the Greater Antilles, Hurricane Ivan struck Aruba as a major category four hurricane in 2004. Before its strengthening and strike on Aruba, Ivan struck Willemstad as a category one hurricane, the only other hurricane striking this island in 106 years other than Hurricane Joan in 1988 which was also a category one storm.

3.3 Tropical Storm and Hurricane Return Periods

For the 106 year dataset, including the years 1901 through 2006, return periods for tropical storm and hurricane strikes were calculated. The goal in calculating a set return period is to determine the average period in which a storm of a certain magnitude is expected to recur once (Chu and Wang 1998). In the future, these data may offer insight on the "chances" of strikes in future hurricane seasons (Muller and Stone 2001). While these calculations provide a useful tool to compare past data, the return periods should not be considered predictions of future strikes (Muller and Stone 2001). Return periods calculated for the twenty-six Caribbean cities chosen in this study demonstrate a range of intervals in which a strike is expected, beginning with the northernmost islands of the study (Figure 3.9).

Return periods for each island's total tropical storms and hurricanes together are fairly evenly distributed. No island exceeds a return period greater than fifteen years for all striking storms with most locations not exceeding five years; however, variations grow widely as storms become more specific in terms of minor or major hurricanes. Return period calculations for striking tropical storms includes all storms striking a particular location, including minor and major hurricanes. The average return period for tropical storms for all twenty-six islands in the study is four years. Return periods for the northernmost islands such as Nassau, Bahamas, are as low as two years while islands in the extreme southern portions of the study area reach up to a fifteen year return periods for a tropical storm or hurricane strike. These southern regions include areas such as Curacao and Aruba, where tropical storm and hurricane strikes are minimal. Seven islands have an average return period of four years for all tropical storm and hurricane strikes, including Santiago de Cuba, Roseau, Kingston, Montego Bay, Negril, Ocho Rios, and Castries.



	Coastal Community		Coastal Community
1	Nassau, Bahamas	14	San Juan, Puerto Rico
2	Georgetown, Bahamas	15	Charlotte Amalie, St. Thomas
3	Nueva Gerona, Cuba	16	The Valley, Anguilla
4	La Habana, Cuba	17	Marigot, St. Martin
5	Santiago de Cuba, Cuba	18	Basseterre, St. Kitts/Nevis
6	Georgetown, Cayman Islands	19	St. John's, Antigua
7	Negril, Jamaica	20	Port Louis, Guadeloupe
8	Montego Bay, Jamaica	21	Roseau, Dominica
9	Ocho Rios, Jamaica	22	Fort-de-France, Martinique
10	Kingston, Jamaica	23	Castries, St. Lucia
11	Port-Au-Prince, Haiti	24	St. George's, Grenada
12	Santo Domingo, Dominican Rep.	25	Willemstad, Curacao
13	Grand Turk, Turks & Caicos	26	Oranjestad, Aruba

Figure 3.9. Spatial distribution of return periods for twenty-six locations over a one hundred six year time period.

Return period calculations for hurricane strikes includes all storms classified from categories one through five. The average return period for all hurricane strikes is ten years, a significant increase from the four year average of tropical storm return periods. In this case, Georgetown, Grand Cayman has the lowest number of years between minor hurricane strikes. This island in particular will experience a hurricane strike, once every five years on average. Both locations included in this study for the Bahamas, Nassau and Georgetown experienced a high return period for hurricanes—five and eight years, respectively. Moving southward in the Greater Antilles, one location in particular stands out. Santiago de Cuba, Cuba has a hurricane return period of fifteen years. In other calculations, this location generally experiences return periods close to, if not below, the average calculated return period for the region. This statistic is true because most storms struck this location as tropical storms. The minor hurricane return periods for both Montego Bay and Negril, Jamaica are eight years; however, Ocho Rios and Kingston's return periods are slightly higher—nine and ten years, respectively. Marigot and St. John are both locations that will experience a hurricane once every four or five years. Hurricane return period durations increase at more southward islands. Martinique and St. Lucia are both islands with hurricane return periods of fifteen years or greater. Curacao and Aruba, though, remain as the islands with return periods indicating the rareness of the storms, with fifty-three years between a striking hurricane for Curacao and thirty-five years between hurricane strikes for Aruba.

The largest return period calculations are for major hurricanes, categories three, four, and five. Major hurricanes obviously had the fewest numbers of total strikes. The average return period of major hurricane strikes for the twenty-six locations in this study is thirty-six years, excluding Willemstad, Curacao which did not experience a major tropical storm in this time period. As was the case for tropical storm return periods, Nassau, Bahamas, experienced the most major hurricane strikes. Consequently, the return period of major hurricanes for Nassau, Bahamas is only ten years. As the geography of islands moves southward, return periods for major hurricanes increases for most cites. Cuba will experience a major hurricane every fifteen to thirty-five years, based on calculations from all three Cuban cities included in this study. Santiago de Cuba experienced the least number of major hurricane strikes on the island, resulting in a return period of thirty-five years. Surprisingly, Georgetown, Grand Cayman experienced only one major hurricane strike within the 106 year dataset. Hurricane Ivan struck this island in 2004, giving this location a 106 year return period for major hurricanes. Two cities in Jamaica will experience a major hurricane every twenty-one years—Kingston and Ocho Rios, while the major hurricane return periods in Negril and Montego Bay is twenty-six years. Moving southward towards Haiti and the Dominican

Republic, return periods for major hurricanes basically remain the same. Haiti's return period calculations are the same as Negril and Montego Bay, Jamaica, as well as the Dominican Republic with a return period of twenty-six years for major hurricanes. Santo Domingo, Dominican Republic experienced four major hurricanes within the 106 year dataset: Hurricane Number Two in 1930, Hurricane Inez in 1966, Hurricane Beulah in 1967, and Hurricane David in 1979. Return periods of major hurricanes continue to fluctuate throughout the Caribbean islands, with a significant decrease to the south of the Dominican Republic. Both Grand Turk and San Juan will experience a storm of this magnitude every seventeen years, while further southeast, St. Thomas will only experience a major hurricane every thirty-five years. A decrease in occurrence rates is evident once again in more south islands such as St. Martin, Anguilla, St. Kitts, Antigua, and Guadeloupe. These islands' major hurricane return periods range from seventeen to twenty-one years. This steady range of return periods is interrupted further south in the Lesser Antilles. Fort-de-France, Martinique has a 106 year return period for major hurricanes, after experiencing Hurricane Allen in 1980 as a category three storm. St. Lucia also has a major hurricane return period of 106 years after experiencing only one major hurricane in the 106 year dataset. A slight decrease in return periods is evident for St. George's Grenada at thirty-five years; however, a severe increase occurs at Willemstad, Curacao which did not experience a major hurricane strike anytime between 1901 and 2006. The return period of major hurricanes at this location can be classified as 106 plus years. Aruba, as the southwestern most island in the dataset, will only experience a major hurricane every 106 years.

Many of the tropical storms and hurricanes that struck in the Caribbean Region moved on to cause deadly destruction on the United States (Table 3.1).

Table 3.1. Top 10 Deadliest U.S. Storms (www.wunderground.com/hurricane/usdeadly.asp).

Rank	Name	Year	Category	Deaths	Strikes in Greater/Lesser Antilles
1	Great Galveston Hurricane (TX)	1900	4	8000	
2	FL (Lake Okeechobee)	1928	4	2500	X
3	Katrina (LA/MS/FL/GA/AL)	2005	3	1350	X
4	Cheniere Caminanda (LA)	1893	4	1100-1400	
5	Sea Islands (SC/GA)	1893	3	1000-2000	
6	GA/SC	1881	2	700	
7	Great Labor Day Hurricane (FL Keys)	1935	5	408	X
8	Last Island (LA)	1856	4	400	
9	Audrey (SW LA/N TX)	1957	4	390	
10	LA (Grand Isle)	1909	4	350	X

The Lake Okeechobee Hurricane in 1928 affected eleven of the twenty-six Caribbean locations in this study before making landfall in the United States as a category four hurricane. Before its final landfall in the United States, this storm affected both Bahamian locations in this study as a major hurricane. Hurricane Katrina caused devastation on the Gulf Coast of the United States; however, it began its path in the Caribbean striking the Bahamas as well as the Cayman Islands as a tropical storm. Similar to Hurricane Katrina, the Great Labor Day Hurricane in 1935 also struck both locations of the Bahamas chosen for this study, as a tropical storm. Hurricane Audrey, however, did not affect any islands in the Caribbean Region before making landfall in the United States. The Grand Isle, LA Hurricane in 1909 affected three Caribbean locations included in this study: Cayman Islands, Jamaica, and

Cuba. Only three cities within these countries experienced a strike from this storm, ranging from a tropical storm to a category one hurricane.

Chapter 4: Influences on Hurricane Strikes

4.1 El Niño—Southern Oscillation

One major factor that influences tropical storm activity throughout the world is the El Niño—Southern Oscillation (ENSO) pattern. As defined by Trenberth (1997), El Niño (Spanish for the “boy Christ child”) was the designated name for the warm, southerly-moving current along the coast of South America near Peru which often occurred during the Christmas season. This process is best described as a fluctuation in the normal occurrences in the ocean-atmospheric structure every few years (Landsea et al. 1999). Although the change in ocean temperature is noticeable in one specific area of the world, climate is affected globally. Within the ENSO, two specific extremes may occur; El Niño and La Niña. A broad description of an El Niño event is the occurrence of warmer than average sea surface temperatures in the Pacific Ocean (Pielke and Landsea 1999). The irregularity in temperature is recognized when sea surface temperatures have reached 0.5ºC (32.9ºF) greater than the average, for six successive months (Bove et al. 1998). This pronounced activity, in turn, produces increased vertical wind shear in the prominent region for tropical storm and hurricane formation, and disturbs the formation and duration of these storms (Landsea et al. 1999). With an increase in vertical wind shear, conditions become hostile for tropical storm formation (Keim et al. 2004). Studies have determined that the probability of a tropical storm or hurricane strike is lessened during an El Niño event, particularly during stronger phases of the cycle (Lyons 2004). An overall 10% decrease in the number of tropical storm and hurricane formations is likely during an El Niño event in the Atlantic region, and only 20% of all storms will actually make landfall (Larson et al. 2005). It is often perceived that only the Atlantic Ocean is strongly affected by this process; however, other regions of the world may experience significant changes in the formation of tropical storms. A strong El Niño event has been proven to decrease landfalling tropical storms and hurricanes along the coast of South China (Liu and Chan 2003). Trenberth (1997) states that El Niño and La Niña events generally last one year, 50% of all years can be designated either an El Niño or a La Niña event.

In contrast, a La Niña event occurs when sea surface temperatures are consistently below average for at least six consecutive months (Bove et al. 1998). Unlike El Niño conditions, La Niña is typically associated with a decrease in vertical wind shear in the Atlantic Basin, therefore allowing tropical storm formation as well as significant growth in the storms (Bove et al. 1998). Muller and Stone (2001) reveal an increase in hurricanes during past La Niña seasons, along with the opposite results during El Niño conditions. Larson et al. (2005) determines that a 15% increase in tropical storm and hurricane formation is likely, on average, during a La Niña event. Additionally, almost one-third of all tropical storms and hurricanes formed during these conditions will make landfall (Larson et al. 2005). With significant increases in tropical storm and hurricane formation, it is inferred that a La Niña event will generate extensively more damage than experienced during El Niño (Keim et al. 2004).

Strong El Niño events recorded in history are reflected in the Caribbean Region hurricane recurrence research in this thesis. Specific years in which intense El Niño events occurred are easily compared to the lack of tropical storm and hurricane strikes for certain time periods in the 106 year dataset included in this research (Table 4.1). In Table 4.1, a slight difference is apparent in the averages numbers of tropical storm and hurricane numbers. The averages for tropical storms, hurricanes, and major hurricanes are all slightly lower during El Niño events than those averages found for the La Niña events. To determine whether or not the frequencies between El Niño and La Niña events are statistically different, the Wilcoxon Rank Sum Test was run. This test failed to reject the null hypothesis, that there is no difference between El Niño and La Niña events in the frequency of storm strikes (p. = 0.29).

Table 4.1. Tropical storm and hurricane strikes during El Niño and La Niña Events from 1950, Averages for August, September, and October (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml) .

El Niño Events from 1950 (Averages August , September, and October) and Caribbean Tropical Storms & Hurricanes			
YEAR	**Tropical Storms**	**Hurricanes**	**Major Hurricanes**
1951	3	3	0
1957	0	0	0
1963	3	2	1
1965	1	1	1
1969	2	1	0
1972	0	0	0
1976	0	0	0
1977	0	0	0
1982	0	0	0
1986	0	0	0
1987	2	1	0
1991	1	0	0
1994	2	0	0
1997	0	0	0
2002	3	2	0
2004	5	3	3
2006	2	0	0
AVG.	**1.5**	**0.8**	**0.3**

La Niña Events from 1950 (Averages August, September, and October) and Caribbean Tropical Storms & Hurricanes			
YEAR	**Tropical Storms**	**Hurricanes**	**Major Hurricanes**
1954	3	0	0
1955	3	2	1
1956	2	1	0
1961	2	0	0
1964	3	2	1
1970	1	0	0
1971	1	0	0
1973	1	0	0
1974	1	0	0
1975	0	0	0
1983	0	0	0
1988	2	2	1
1995	4	3	1
1998	1	1	1
1999	4	3	1
AVG.	**1.9**	**1**	**0.4**

For example, in 1957, no tropical storm or hurricane strikes were recorded for any locations at the twenty-six cities in this study. This particular year, along with 1958, is considered a strong El Niño event for the first half of this year (Glantz 1998) (Figure 4.1). In 1958, two storms struck in the Caribbean Region—Hurricanes Ella and Janice. Ella initially struck Roseau, Dominica as a tropical storm before heading northwestward towards the Dominican Republic and Haiti. This storm struck Santo Domingo as a tropical storm before strengthening to a category one hurricane when striking Port-Au-Prince. Finally, Hurricane Ella intensified again before striking Cuba as a category three storm. Hurricane Janice struck as a tropical storm on Nassau, Bahamas, which was the only island in this study affected by this particular system. The year 1972 was also considered a significant El Niño event which is apparent in this study (Glantz 1998) (Figure 4.2). In this year, no tropical storm or hurricane struck any of the twenty-six Caribbean locations. 1982 and 1983 were also strong El Niño years, both in which no tropical storm or hurricane struck any of the twenty-six Caribbean locations in this study (Glantz 1998) (Figure 4.3). The year 1983 was considered an El Niño year, for the first portion of the year. However, after experiencing a neutral phase, the remainder of the year from August through December was considered a La Niña event http://www.cpc.ncep.noaa.gov/products/analysis_monitoring /ensostuff/ ensoyears.shtml). In 1991, Tropical Storm Fabian struck Nueva Gerona, Cuba and did not affect any other location. This year was determined an El Niño event. One additional significant El Niño event took place during 1997 (Glantz 1998) (Figure 4.4).

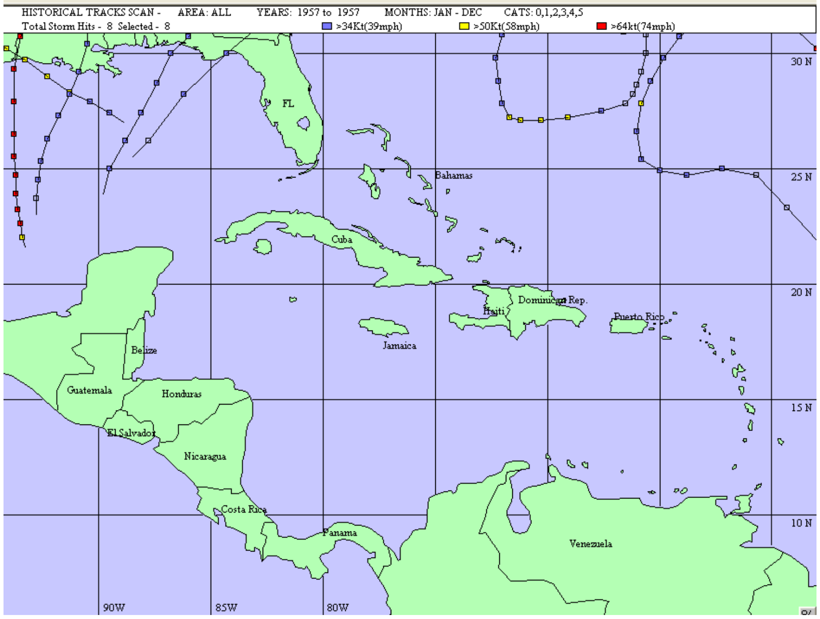
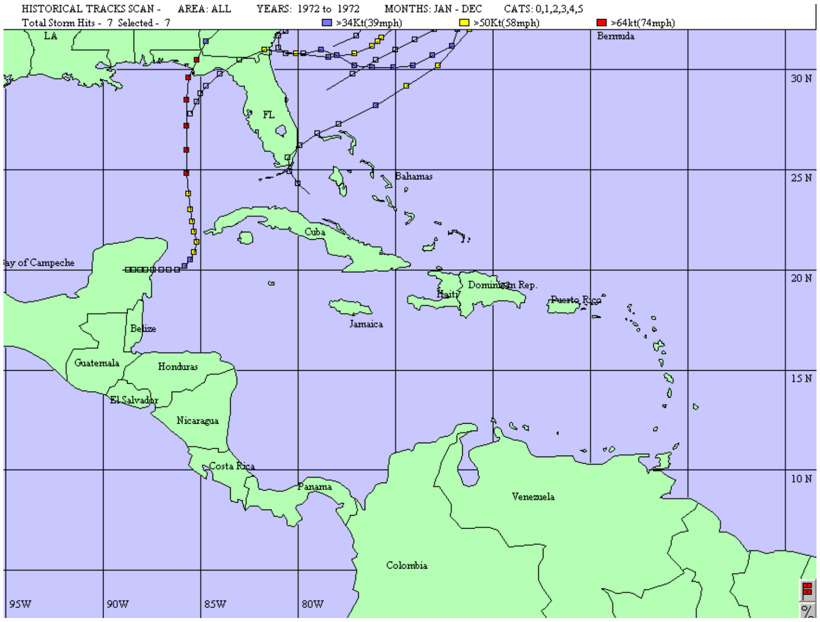
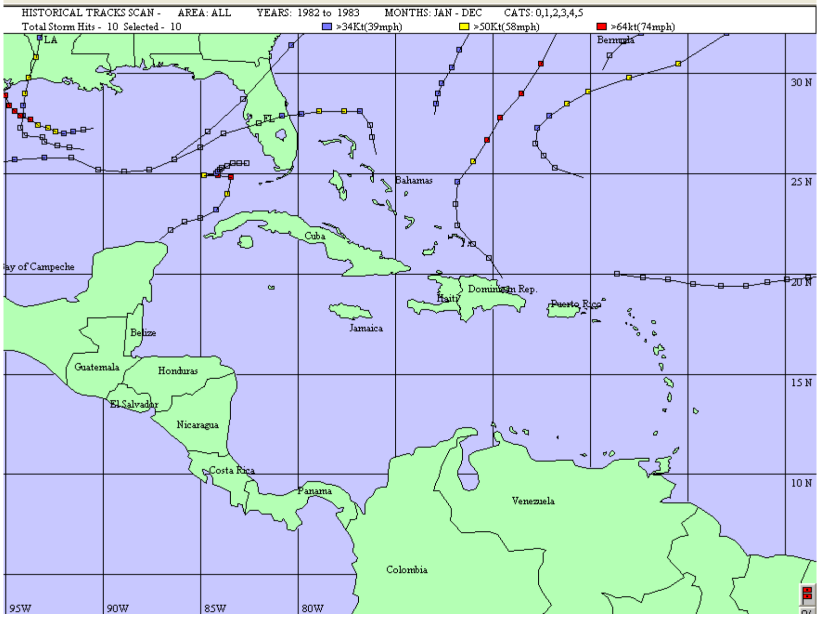


Figure 4.1. Tropical storm and hurricane tracks, 1957. Source: Hurrevac Program.


HISTORICAL TRACKS SCAN - AREA: ALL YEARS: 1972 to 1972 MONTHS: JAN - DEC CATS: 0,1,2,3,4,5

Total Storm Hits - 7 Selected - 7

Figure 4.2. Tropical storm and hurricane tracks, 1972. Source: Hurrevac Program.


HISTORICAL TRACKS SCAN - AREA: ALL YEARS: 1982 to 1983 MONTHS: JAN - DEC CATS: 0,1,2,3,4,5

Total Storm Hits - 10 Selected - 10

Figure 4.3. Tropical storm and hurricane tracks, 1982-1983. Source: Hurrevac Program.

During this year, no storms affected the Caribbean locations in this study. Hurricane Erika came close to striking the Caribbean islands; however, the storm re-curved toward the north-northeast.

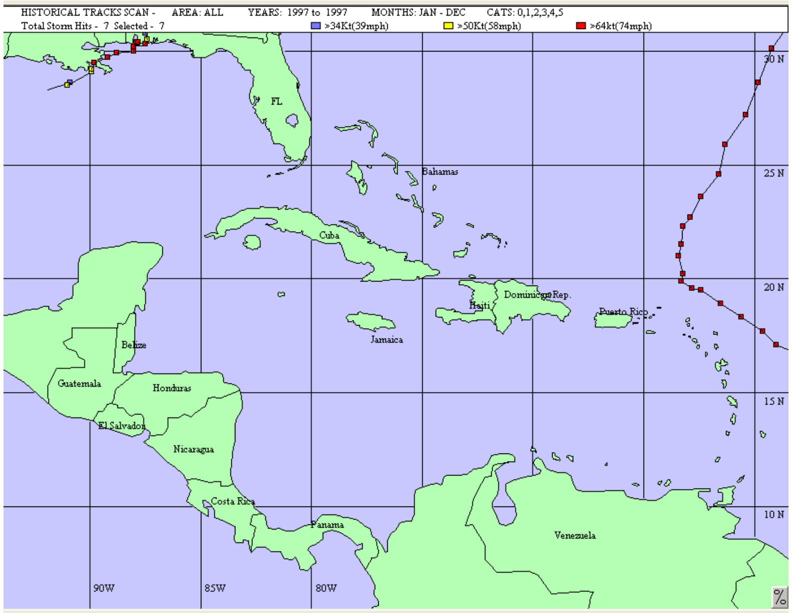


Figure 4.4. Tropical storm and hurricane tracks, 1997. Source: Hurrevac Program.

Similar to specific El Niño years, increases in hurricane activity during significant La Niña events are apparent in this research. The year 1909 was considered a moderate La Niña event on record (Glantz 1998) (Figure 4.5). Five storms struck that year, at the twenty-six locations in this study. Hurricane Number Six struck eight different locations in the Caribbean Region, including Antigua, Cuba, Dominican Republic, Haiti, Puerto Rico, St. Kitts/Nevis, and St. Thomas. This storm's peak strike strength in the Caribbean Region was a category two hurricane striking Nueva Gerona, Cuba. Other storms during 1909's La Niña event included the Velasco Hurricane, Tropical Storm Number Five, the Grand Isle Hurricane, Hurricane Number Ten, and Hurricane Number Eleven. Also considered a significant La Niña event was 1916, in which six storms affected areas within the twenty-six Caribbean locations in this study (Glantz 1998) (Figure 4.6). During August, one of the peak months of hurricane season, Hurricane Number Four formed in the Atlantic Ocean. Eight Caribbean islands were affected by this storm, which first struck Castries, St. Lucia as a category one hurricane. This storm's next strike occurred at Fort de France, Martinique, after it strengthened into a category two hurricane. Some slight weakening took place before the

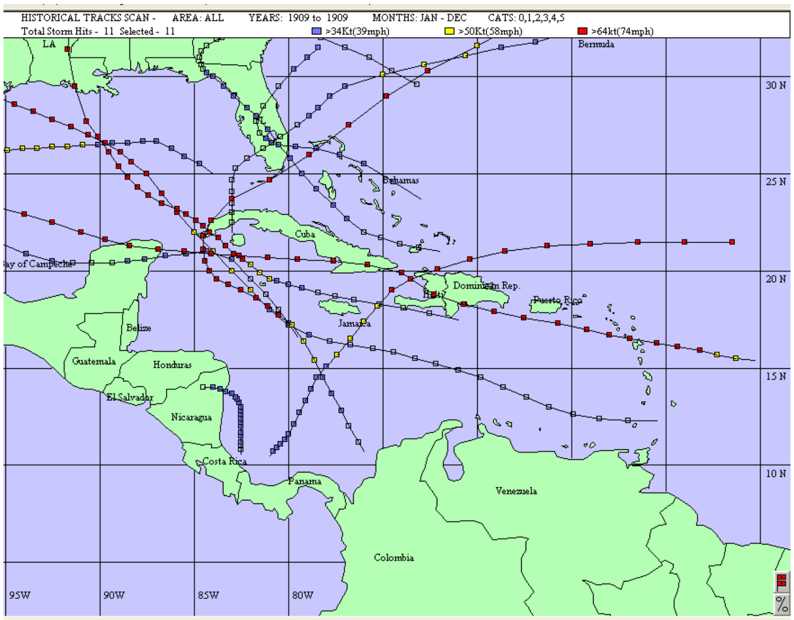


Figure 4.5. Tropical storm and hurricane tracks, 1909. Source: Hurrevac Program.

storm made struck Roseau, Dominica as a tropical storm. Hurricane Number Eight moved over the Caribbean waters, which allowed for strengthening before striking the island of Jamaica. All four Jamaican locations included in this study were affected by this storm, which struck as a category two storm at Kingston, Ocho Rios, and Montego Bay; however, Negril only experienced category one force winds.

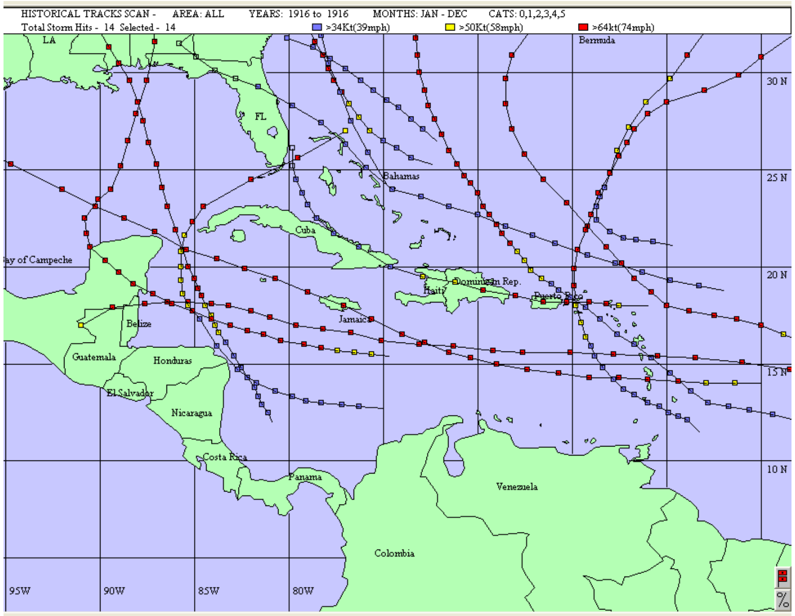


Figure 4.6. Tropical storm and hurricane tracks, 1916. Source: Hurrevac Program.

This same year, Hurricane Number Five struck six different locations in the Caribbean Region: Antigua, Cuba, Dominican Republic, Puerto Rico, St. Martin, and St. Thomas. Four of these locations experienced this storm as a category one, while two only experienced tropical storm force winds. Between the years 1901 and 2006, 1933 was the year with the most tropical storms and hurricanes to affect the twenty-six locations in this study (Figure 4.7). Ten different tropical storms struck one or more islands during this year, which was considered a moderate La Niña event (Glantz 1998). Only one of these storms during this time struck as a major hurricane, on one island in the study. Hurricane Number Twelve's path did not cross many islands in this study; however, it did strike Grand Turk, Turks and Caicos, as a category two storm before striking Nassau, Bahamas as a category four hurricane. Georgetown, Bahamas only experienced tropical storm force winds as a result of Hurricane Number Twelve passing to the northeast of the island. Another storm in 1933 stands out in that it struck both Curacao and Aruba, the two locations that experienced the least numbers of storm strikes. Hurricane Number Two struck both islands as a tropical storm before

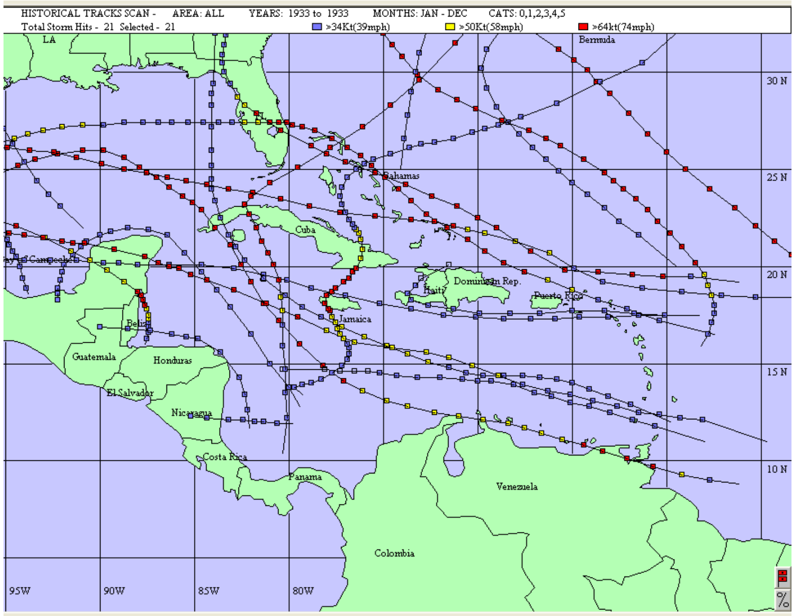


Figure 4.7. Tropical storm and hurricane tracks, 1933. Source: Hurrevac Program.

strengthening, moving northward, and striking both Nueva Gerona, Cuba and Georgetown, Cayman Islands. Hurricane Number Nineteen, the third to last storm of this particular season, struck only one island in this study—Jamaica. This storm struck both Montego Bay and Negril as a category two storm, and only affected Ocho Rios with tropical storm force winds. Only four locations in this study, all located in the middle portion of the Lesser Antilles, were not affected by a tropical storm or hurricane during 1933. These locations include the islands of Dominica, Guadeloupe, Martinique, and St. Lucia. Other significant La Niña events are apparent in this study, including 1949 when five storms struck one or more of the Caribbean locations in this study (Figure 4.8).

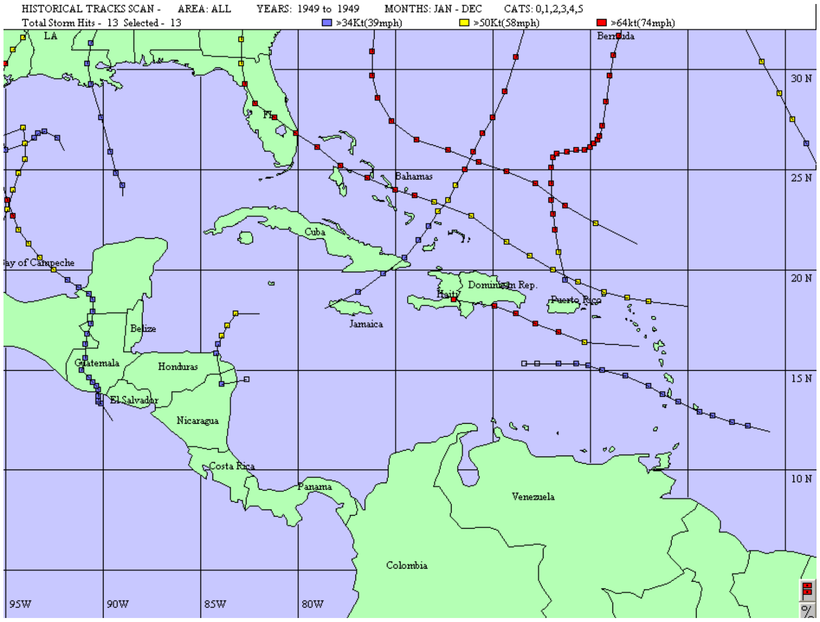


Figure 4.8. Tropical storm and hurricane tracks, 1949. Source: Hurrevac Program.

4.2 Global Warming

Tropical storm and hurricane strike frequencies have been studied for numerous years with many different objectives. Most importantly, studying the past strikes of tropical storms and hurricanes can provide insight into the future frequency of these storms and perhaps aid cities in future preparations for all tropical storms (Jagger et al. 2001). All locations affected by tropical storms and hurricanes are important in this type of research; however, areas such as the United States and the Caribbean Region seem especially vulnerable with constant increases in population, tourism, and coastal building (Lyons 2004). Numerous studies have been conducted to determine the causes and implications of increased hurricane activity experienced in recent years over the Caribbean Sea and the Gulf of Mexico. However, differences in opinion have resulted in dynamic debates throughout the world regarding this topic (Webster et al. 2005). The notion of global warming affecting hurricane frequency and intensity is the focus of Webster's paper. Three different aspects of the effects of global warming on hurricanes have been included in other research: sea surface temperature change, increased coastal populations, and human-induced change through means of emitting greenhouse gases. In the future, though, research in this area may not only aide hurricane forecasters in predicting future hurricane strikes, but may also be important in the emergency management sector for hazard mitigation and emergency planning as well as providing a means for protecting the environment (Jagger et al. 2001).

Tropical storms and hurricanes most often form in ocean regions where sea surface temperatures reach over 26º C (78.8 º F); however, oceans vary in temperature over time (Trenberth 2005). It is not determined, though, to what extent ocean temperature changes affect the make-up of a tropical storm or hurricane (Cione and Uhlhorn 2003). Multidecadal cycles in tropical storms are influenced by these fluctuations in sea surface temperatures; however, these cycles may not be the sole influence on tropical storm and hurricane formation (Goldenberg et al. 2001). In some instances, an increase in sea surface temperatures has led to a pronounced increase in tropical activity (Franklin et al. 2006). Many studies focus on the insinuation that global warming impacts sea surface temperatures, consequentially impacting the formation of tropical storms and hurricanes. For example, it is mentioned in Landsea et al. (1999) that prior research portrayed that a "greenhouse-warmed climate" produces an increase in sea surface temperatures. This information, though, does not provide direction in determining potential changes in the frequency of tropical storms and hurricanes (Landsea et al. 1999). Studies of sea surface temperatures and trends, regarding tropical storms and hurricanes, were also mentioned by Webster et al. (2005) in that no trends are significant when compared to the influence attributed to interannual variability. However, various research concentrates solely on the Atlantic regions, where only 12% of the world's tropical storms form, and do not account for typhoons in the Pacific Ocean region (Schiermeier 2005). Typhoons in the Pacific react differently to changes in sea surface temperature than tropical storms and hurricanes in the Atlantic region (Schiermerier 2005). In a study conducted that simulated a human-induced warmer climate, research determined an increase in hurricane activity is possible due to higher sea surface temperatures (Knutson et al. 1998).

In the ongoing deliberation of whether global warming has an effect on the increase of sea surface temperatures, numerous debates have emerged. One author questioned another's research which stated that human-induced climate change "has the potential for slightly increasing the intensity of tropical storms and hurricanes through warming of sea surface temperatures" (Landsea 2005, p. E-11). Landsea (2005) states that the time series to be included in a study of this magnitude must cover a more extensive period of time to be sufficient. Arguments included that hurricane activity is less intense than that of the mid 1900s and that there is no evidence of a connection between hurricane activity and global warming (Landsea 2005). On the other side of the debate, though, a warmer, moister globally warmed world would result in increased hurricane activity along with a direct impact on sea surface temperatures (Anthes et al. 2006). If sea surface temperatures are proven to affect tropical storm and hurricane frequency and/or intensity, it is insignificant relative to natural variability in the cycle of hurricane formation (Pielke et al. 2006).

As many researchers attempt to determine whether global warming has an effect on hurricanes, the perception of an increase in the destruction caused by hurricanes is a recurring concept. The notion is apparent that as global warming will increase the frequency and intensity of hurricanes, hence greater destruction would ensue. When statements are made regarding the differences in hurricane destruction today as opposed to fifty years ago, population patterns and demographics must be taken into consideration (Pielke and Landsea 1998). One simple answer is true in this regard—hurricanes cause more damage along the coast today than in the past because there is a larger population in these regions, along with a significantly larger amount of expensive structures (Pielke and Landsea 1998). Societies in all areas of the world, especially coastal regions such as the Caribbean, where tourism is often the lead industry, are increasingly vulnerable to the destruction of a hurricane strike. Not only are populations along the coast constantly growing, but high property values cause hurricane damage to be more costly (Anthes et al. 2006). Changnon (2003) showed that increased losses sustained from a passing hurricane are to be blamed on societal changes, not global warming. Society has become more vulnerable to these types of situations, and people continue to relocate in hazard-prone areas. With tourism as a major part of the much of the Caribbean's economy, locations along the coastal regions have experienced a vast expansion of population as well as an increase in the infrastructure of these areas (Pielke et al. 2006). Before direct statements can be made regarding the impact of global warming on hurricanes, increased destruction in largely populated coastal areas must be taken into consideration. Uncertainties are apparent as to whether global warming increases hurricane frequency and intensity. However, the continual growth of population in coastal areas allows for potential devastation if the particular region lies in the path of tropical storm or hurricane.

“Greenhouse gas-induced climate warming could affect hurricanes in a number of ways, including changing their intensity, frequency, and locations of occurrence” (Knutson et al. 1998 p. 1018). With global warming debates becoming more intense among researchers, one general idea can be agreed upon: greenhouse gases are most certainly increasing (Balling and Cerveny 2003). This increase in the amount of greenhouse gases may, in turn, cause a warming of the climate. If the climate is persistently warmed, an increase in sea surface temperatures is probable (Landsea et al. 1999). Researchers have analyzed data to determine if there is a direct correlation between increased greenhouse gas emissions and hurricane intensity and frequency. Trenberth (2005) states that a trend is apparent over the past thirty-five years in the extratropical North Atlantic, in that the increasing of sea surface temperatures is directly caused by global warming which can be attributed to human action. However, he believes that there is no evidence that human-induced climate change has affected the number of hurricanes or where they strike. Other research contributes to the conception of increasing sea surface temperatures as a result of human activity. Anthes et al. (2006) states that the recently observed increases in ocean temperature are projected to continue as greenhouse gas emissions persist.

Assessing the opposite side of the debate on global warming’s effect on hurricanes; some research has found no relationship between the two. In association with the natural variability in the cycle of tropical storms and hurricanes, research shows that an increase in hurricane activity as a result of human-induced global warming, if any, is insignificant when compared to that of the natural cycle of variability in tropical storm formation, frequency, and intensity (Pielke et al. 2006). Pielke et al. (2006) mentions that previous studies show no evidence implying that an atmosphere affected by greenhouse gas emissions will produce major changes in the locations of tropical storms and hurricanes. Research suggests that tropical storm changes in intensity and frequency are influenced exclusively by multi-decadal variations, with no considerable trends attribute to global warming (Balling and Cerveny 2003).

In analyzing the return periods of tropical storms and hurricanes in the Caribbean Region, a trend should be apparent in the most recent years of the dataset if global warming was a contributing factor in tropical storm and hurricane activity. However, the time period in this study with the most significant tropical storm and hurricane strikes are during the 1920s and early 1930s. A small lapse in tropical storm and hurricane strikes took place in the late 1930s and early1940s, before another increase in the late 1940s and throughout the 1950s. Tropical storm and hurricane activity slowly picked up in the 1990s through 2006; however, numbers are far from those experienced in the late 1920s, early 1930s. If global warming were a factor in the frequency and intensity of tropical storms and hurricanes, a major increase in the number of storm strikes would be expected in this study.

Chapter 5: Summary and Conclusions

This chapter provides a brief summary of the objectives as well as the conclusions of this thesis. All objectives will be reviewed along with its subsequent results and conclusions. Possible future research topics will also be discussed within this chapter.

5.1 Review: Objectives, Methods, and Study Area

Islands throughout the Caribbean Region repeatedly experience tropical storm activity every summer and autumn between June and November and are often severely affected by the these storms' strikes. Consequently, this thesis examines the climatology of past strikes of tropical storms and hurricanes in the Caribbean Region over the past 106 years, specifically the largely populated coastal cities on islands including the Bahamas, Jamaica, Cuba, Puerto Rico, the Virgin Islands, and the Windward and Leeward Islands extending to Aruba. The principal objectives of this study are:

1) To produce a time series of historical tropical storm or hurricane strikes at each island chosen in the Caribbean Region and characteristics of the storm at the time of strike (i.e. Category of storm, winds, etc.).

2) To calculate the annual return periods of tropical storms, minor hurricanes, and major hurricanes for each of the locations chosen for the study.

3) To provide possible explanations of the results determined in this study.

The extent of this research covers twenty-six islands throughout the Caribbean Region, determined by largely populated cities, or the coastal cities that experience significant numbers of tourists each year. Data were collected on past tropical storm and hurricane strikes for each location over the past 106 years (1901 through 2006). A Hurricane Strike Model is used to determine tropical storm and hurricane strikes within the cities, because the variability of each storm size is not adequately measured and documented (Keim et al. 2007).

Using this model, each storm strike over this period of time was analyzed to determine the strength of winds at a specific location. Based on these conclusions, return periods were calculated for each city chosen in the Caribbean Region according to the number of years in the dataset and the number of strikes for the particular location. After determining the return periods of all tropical storms during the specified time period, an analysis of possible causes of storm frequency and/or intensity including the notion of El Niño—Southern Oscillation and global warming.

5.2 Objective One—Time Series and Storm Strike Characteristics

The first objective was to produce a time series of historical tropical storm or hurricane strikes at each island chosen in the Caribbean Region and characteristics of the storm at the time of strike (i.e. Category of storm, winds, etc.). Twenty-six cities located throughout the islands of the Caribbean were chosen for this study, to determine how many tropical storms and hurricanes struck there. Tropical storm data includes 106 years, from 1901 through 2006.

All tropical storm and hurricane data were mapped for each location chosen for this study based on the strength of the storm, including tropical storms, minor hurricanes (categories one and two), and major hurricanes (categories three, four, and five). Once all storms were catalogued, return period calculations were made for each location based on the number of storms that struck and the number of years in the study.

The distribution of striking tropical storms and hurricanes by year provides insight on the active years, possibly due to La Niña, within the 106 year dataset as compared to the inactive years, possibly a result of El Niño conditions (Landsea et al. 1999). Results show the spatial characteristics of striking tropical storms in that extreme southern portions of the Caribbean are affected the least by passing tropical storms and hurricanes. Moving northward into the Lesser Antilles, tropical storm and hurricane strike activity increases significantly as well as into the Greater Antilles northwestward. A significant number of tropical storm and hurricane strikes are apparent in the early portion of the 106 year dataset, with fluctuations throughout the remaining years. The islands in the Caribbean Region experienced numerous tropical storm and hurricane strikes during the late 1920s and early 1930s, especially around the Bahamas and both the Greater and Lesser Antilles. The late 1950s and early 1960s were another time period in which numerous tropical storms and hurricanes struck in the Caribbean Region. Finally, a significant increase in tropical storm strikes is apparent in the 1990s and early 2000s. The majority of storms during this time did not strike the Bahamas—the bulk of the storms striking in the 1990s were located in the Lesser Antilles, while the Greater Antilles were the focal points for the early 2000s.

5.3 Objective Two—Calculate Return Periods

The second objective was to calculate the annual return periods of tropical storms, hurricanes, and major hurricanes for each of the locations chosen for the study. Historical tropical storm and hurricane data were collected for each of the twenty-six cities throughout the Caribbean Region, over the past 106 years. Using the Hurricane Strike Model, each storm strike over this period of time was analyzed to determine the strength of winds at a specific location. Based on these conclusions, return periods were calculated for each city in the Caribbean Region according to the number of years in the dataset and the number of strikes for the particular location. Calculations were determined for all strikes including tropical storms, hurricanes, and major hurricanes.

Coinciding with the spatial distribution and number of striking tropical storms and hurricanes, return periods for each island vary within this study. Tropical storm and hurricane return periods range from two years in Cuba to fifteen years in Curacao, the island that experienced the least number of storm strikes. The average tropical storm return period for all storms and all points in the region is four years. The regional average return period for hurricanes is eleven years, with the highest calculation being fifty-two years for Willemstad, Curacao and the lowest at four years for Nueva Gerona, Cuba. Finally, the regional average return period for major hurricane strikes is thirty-six years. Nassau, Bahamas experienced the highest number of striking major hurricanes; therefore the return period of major hurricanes at this location is only ten years. In contrast, though, to Nassau is Willemstad, Curacao, a location not struck by a major hurricane in the past 106 years. The return period of a storm of this strength is 106 years plus.

5.4 Objective Three—Explanation of Results

Objective number three was to provide possible explanations of the results determined in this study. Numerous studies have been conducted to determine the causes and implications of increased hurricane activity experienced in recent years in the Caribbean Sea and the Gulf of Mexico. Two topics in particular are discussed in this thesis: El Niño/La Niña and global warming.

Tropical activity can be highly influenced throughout the world by the El Niño—Southern Oscillation (ENSO) pattern. This process may be described as a fluctuation in the normal occurrences in the ocean-atmospheric structure every few years in the tropical Pacific (Landsea et al. 1999). Two different situations may occur within this phase: El Niño, when sea surface temperatures in the tropical Pacific Ocean are warmer than normal, or La Niña, when sea surface temperatures in the tropical Pacific Ocean are cooler than normal. Decreased hurricane activity is often associated with the El Niño phase, due to increased vertical wind shear, while increased tropical activity is often experienced during the La Niña phase. Significant El Niño and La Niña phases in history are apparent in this thesis where certain years are associated with either decreased tropical storm or hurricane strikes or years where strikes are numerous.

Three different aspects of the effects of global warming on hurricanes have been included in other research: sea surface temperature change, increased coastal populations, and human-induced change through means of emitting greenhouse gases. Many studies suggest that global warming impacts sea surface temperatures, consequentially impacting the formation of tropical storms and hurricanes. Debates arise on whether global warming will contribute to increases in sea surface temperatures or if the temperatures fluctuate based on a natural cycle. However, if sea surface temperatures are proven to affect tropical storm and hurricane frequency and/or intensity, it is insignificant relative to natural variability in the cycle of hurricane formation (Pielke et al. 2006). When statements are made regarding the differences in hurricane destruction today as opposed to fifty years ago, population patterns and demographics must be taken into consideration (Pielke and Landsea 1998). The continual growth of population in coastal areas allows for the potential of massive destruction if the particular region lies in the path of a tropical storm or hurricane. Some research has determined that human-induced climate change "has the potential for slightly increasing the intensity of tropical cyclones through warming of sea surface temperatures" (Landsea 2005). Greenhouse gases are certainly increasing (Balling and Cerveny 2003); however, there is no evidence that human-induced climate change has affected the number of hurricanes or where they strike (Trenberth 2005). A peak in tropical storm and hurricane strikes was determined in this study, in the 1930's. However, after this time period, a significant decrease in storm strikes took place until an increase began in the early 1990's. The increase of tropical storm activity in the Caribbean Region within the past three to four years could be an implication of increased sea surface temperatures, correlated with increasing population, resulting in increased greenhouse gas emissions. While some researchers believe that global warming has a significant impact on the frequency and intensity of tropical storms and hurricanes, this study shows no apparent trend. While tropical storm and hurricane strike frequency increases around the year 2000, numbers are not comparable to those experienced in the earlier portion of the dataset.

5.5 Future Research

Research on tropical storm and hurricane recurrences may be continued with each passing hurricane season. Additional islands may be included in future research to increase the study area as well as adding additional years. Research on this topic is necessary to increase standards in preparedness as well as hazard mitigation planning.

A more specific focus on the causes and implications of tropical storm and hurricane strikes is an important research topic. Global warming and the El Niño—Southern Oscillation phase were not the focus of this thesis; however, additional research on these topics would be useful. Comparisons may be made between Caribbean storms and other areas of the world that experience tropical storms and hurricanes.

Another possibility would be to determine return periods of striking tropical storms and hurricane in other areas of the world, such as China, Japan, and the western coast of Mexico. Comparisons could also be made in research such as this with areas like the Caribbean Region and the Gulf of Mexico. Any research that contributes to the understanding of tropical storm strikes would benefit scientists as well as those that live in coastal areas that frequently experience destruction from these storms.

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Appendix A: Tropical Cyclone Strikes for Twenty-Six Caribbean Locations—Year, Storm Type, Storm Name (Alphabetical Order by Country)

The Valley, Anguilla 18.1°, 63.1°

1901 TS 7
1906 H2 4
1908 TS 1
1916 H1 5
1916 TS 12
1922 H2 2
1924 H1 3
1928 H3 Lake Okeechobee
1931 H1 6
1932 H3 7
1933 TS 16
1938 TS 1
1943 TS 2
1947 TS 9
1949 TS 2
1950 H1 Dog
1953 TS Edna
1954 TS Alice
1955 TS Hilda
1960 H4 Donna
1966 H1 Faith
1979 TS Claudette
1979 TS Frederic
1989 H3 Hugo
1995 H4 Luis
1995 TS Marilyn
1996 H1 Bertha
1998 H1 Georges
1999 H1 Jose
1999 H3 Lenny

St. John's, Antigua 17.1°, 61.5°

1901 TS 7
1906 H2 4
1908 TS 8
1909 H1 6
1910 H1 3
1915 H1 Galveston
1922 H1 2
1924 H1 3
1928 H3 Lake Okeechobee
1930 H1 2
1932 H1 7
1932 TS 10
1933 TS 3
1933 TS 5
1933 TS 16
1934 TS 7
1950 H2 Baker
1950 H2 Dog
1954 TS Alice
1960 H3 Donna
1963 TS Helena
1964 H3 Cleo
1966 TS Faith
1966 H2 Inez
1979 H2 David
1979 TS Frederic
1989 H4 Hugo
1990 H1 Klaus
1995 TS Iris
1995 H4 Luis
1995 TS Marilyn
1996 H1 Bertha
1998 H3 Georges
1999 H2 Jose
1999 TS Lenny
2000 H1 Debby
2006 TS Chris

Oranjestad, Aruba 12.5°, 70.0°

1911 TS 4
1932 H1 10
1933 TS 2
1954 TS Hazel
1955 TS Janet
1961 TS Anna
1971 TS Edith
1988 TS Joan
1996 TS Cesar
2004 H3 Ivan
2005 H1 Emily

Nassau, Bahamas 25.0°, 77.3°

1901 TS 4
1906 TS 4
1906 TS 8
1908 TS 6
1908 H2 8
1916 TS 8
1919 H2 2
1923 TS 2
1926 H4 1
1926 H3 6
1928 H1 1
1928 H4 Lake Okeechobee
1929 H3 2
1932 H5 4
1933 TS 5
1933 H4 12
1933 H2 18
1935 H2 Great Labor Day
1936 TS 5
1937 TS 3
1937 TS 8
1941 H2 5
1945 TS 11
1946 H3 9
1946 TS 4
1946 TS 6
1947 TS 7
1949 H4 2
1950 TS King
1952 H2 Fox
1956 TS Betsy
1958 TS Janice
1960 H2 Donna
1964 H1 Cleo
1965 H3 Betsy
1966 TS Inez
1979 TS David
1984 TS Isidore
1992 H4 Andrew
1999 H1 Floyd
2001 H1 Michelle
2005 TS Katrina

Georgetown, Bahamas 23.5°, 75.8°

1901 TS 11
1903 TS 3
1906 TS 2
1906 TS 4
1906 TS 11
1908 H3 6
1908 H1 8
1919 H2 2
1923 TS 2
1926 H4 1
1926 H4 6
1928 H3 Lake Okeechobee
1931 TS 8
1932 TS 3
1932 H2 4
1932 H3 10
1933 TS 11
1933 TS 12
1934 TS 10
1935 TS Great Labor Day
1936 TS 5
1937 TS 2
1942 TS 9
1945 H3 9
1946 TS 6
1949 TS 2
1952 H2 Fox
1956 TS Carla
1960 H3 Donna
1973 TS Gilda
1979 H1 David
1981 TS Katrina
1995 H1 Erin
2005 TS Rita

Georgetown, Cayman Islands 19.3°, 81.4°

1903 H3 2
1909 TS Velasco
1909 TS 5
1909 TS 8
1909 H1 10
1910 TS 3
1910 H1 5
1912 TS 6
1915 H1 Galveston
1915 H1 4
1915 H1 New Orleans
1916 H1 4
1916 TS 6
1922 TS 3
1926 TS 10
1927 TS 6
1927 TS 7
1932 H2 10
1933 H1 2
1933 TS 3
1933 TS 6
1933 TS 18
1939 H1 5
1944 H1 11
1948 H1 7
1951 H2 Charlie
1951 H1 Item
1952 H2 Fox
1955 TS 5
1955 H1 Hilda
1969 TS Camille
1974 TS Carmen
1980 H1 Allen
1981 TS Katrina
2004 H1 Charley
2004 H4 Ivan
2005 H2 Emily

La Habana, Cuba 23.1°, 82.4°

1902 TS 1
1906 H2 8
1909 H2 19
1910 H3 5
1915 TS Galveston
1915 TS 4
1917 H2 3
1919 H2 2
1924 TS 7
1926 H3 10
1930 TS 2
1933 H1 11
1933 H2 18
1944 H3 11
1945 TS 7
1946 H2 5
1948 H2 7
1948 H4 8
1950 H1 Easy
1964 H2 Isbell
1966 H2 Alma
1968 TS Gladys
1969 TS Camille
1979 TS Frederic
1985 TS Elena
1985 H1 Kate
1987 TS Floyd
1996 TS Lili
1999 TS Irene
2002 TS Lili
2004 H3 Charley
2004 H1 Ivan
2005 H1 Dennis
2005 TS Rita

Nueva Gerona, Cuba 21.8°, 82.8°

1901 TS 2
1901 H1 7
1902 TS 1
1903 H1 2
1906 H3 8
1906 TS 11
1909 H2 9
1909 H1 8
1909 H1 10
1910 TS 3
1910 H3 5
1915 H3 Galveston
1915 H1 4
1915 TS New Orleans
1917 H3 3
1922 TS 3
1926 H3 10
1933 H1 2
1933 TS 6
1944 H3 11
1945 TS 7
1946 H1 5
1947 TS 6
1948 TS 7
1948 H2 8
1950 TS Baker
1950 H1 Easy
1952 TS Fox
1953 TS Alice
1953 TS 3
1955 TS 5
1966 H2 Alma
1968 H1 Gladys
1969 H2 Camille
1979 TS Frederic
1980 H4 Allen
1991 TS Fabian
1996 H1 Lili
1999 TS Irene
2001 H2 Michelle
2002 H2 Isidore
2002 H2 Lili
2004 H2 Ivan

Santiago de Cuba, Cuba 20.0°, 75.8°

1901 TS 2
1901 TS 7
1908 TS 8
1909 H1 6
1912 TS 7
1916 TS 5
1917 TS 3
1924 TS 8
1927 TS 6
1928 TS 2
1930 TS 2
1933 TS 19
1935 TS 5
1939 TS 5
1942 TS 9
1949 TS 11
1955 TS Hilda
1958 H3 Ella
1963 H3 Flora
1964 H2 Cleo
1966 H2 Inez
1994 TS Gordon
1998 H1 Georges
2005 H3 Dennis
2006 TS Ernesto

Willemstad, Curacao 12.1°, 68.6°

1933 TS 2
1954 TS Hazel
1963 TS Flora
1988 H1 Joan
1996 TS Cesar
2004 H1 Ivan
2005 TS Emily

Roseau, Dominica 15.3°, 61.4°

1901 TS 3
1903 H2 2
1908 TS 8
1910 TS 1
1916 TS 2
1916 TS 4
1916 H1 6
1918 TS 5
1924 TS 2
1926 TS 1
1930 H1 2
1931 TS 4
1945 TS 3
1950 TS Baker
1951 TS Charlie
1956 TS Betsy
1958 TS Ella
1960 TS Abby
1963 H1 Edith
1964 H3 Cleo
1966 H1 Inez
1979 H4 David
1980 H2 Allen
1988 TS Gilbert
1989 H2 Hugo
1995 H1 Marilyn

Santo Domingo, Dominican Republic 18.5°, 69.9°

1901 TS 7
1903 TS 2
1909 H1 6
1910 TS 3
1915 TS Galveston
1916 TS 5
1918 TS 5
1921 H1 3
1928 TS 1
1928 H1 Lake Okeechobee
1930 H4 2
1931 TS 6
1932 TS 1
1932 H1 7
1933 TS 16
1945 TS 3
1949 H1 9
1952 TS Charlie
1958 TS Ella
1963 H1 Edith
1963 TS Flora
1964 H2 Cleo
1966 H3 Inez
1967 H3 Beulah
1979 H5 David
1979 TS Frederic
1980 H2 Allen
1985 TS Isabel
1987 H2 Emily
1998 H2 Georges
2003 TS Odette

St. George's, Grenada 12.04°, 61.4°

1901 TS 5
1905 TS 1
1918 H1 2
1928 TS 1
1933 TS 7
1938 TS 2
1954 TS Hazel
1955 H3 Janet
1961 TS Anna
1963 H3 Flora
1978 TS Cora
1980 H1 Allen
1988 TS Joan
1990 TS Arthur
2004 TS Earl
2004 H3 Ivan
2005 H1 Emily

Port-Louis, Guadeloupe 16.3°, 61.3°

1903 TS 2
1906 TS 4
1915 H1 Galveston
1916 TS 2
1916 H1 6
1917 TS 3
1922 TS 2
1924 H1 3
1928 H3 Lake Okeechobee
1930 H2 2
1932 TS 10
1934 TS 4
1934 TS 7
1950 H3 Baker
1950 H1 Dog
1951 TS Charlie
1956 H1 Betsy
1959 TS Edith
1960 H2 Donna
1961 TS Frances
1964 H4 Cleo
1966 H3 Inez
1979 H3 David
1980 H2 Allen
1981 TS Gert
1989 H4 Hugo
1995 H1 Luis
1995 TS Marilyn
1996 TS Hortense
1998 H2 Georges
1999 H1 Jose

Port-Au-Prince, Haiti 18.5°, 72.3°

1901	TS	7
1903	H1	2
1908	H1	8
1909	H1	6
1909	TS	11
1910	TS	3
1915	H1	Galveston
1917	TS	3
1928	TS	2
1931	TS	6
1932	TS	7
1933	TS	16
1938	TS	8
1944	H1	4
1948	TS	1
1949	TS	9
1954	TS	Hazel
1955	TS	Hilda
1958	H1	Ella
1958	TS	Gerda
1963	H3	Flora
1964	H4	Cleo
1966	H3	Inez
1967	TS	Beulah
1979	H1	David
1980	H4	Allen
1987	TS	Emily
1988	H1	Gilbert
1998	TS	Georges
2005	TS	Alpha

Kingston, Jamaica 17.0°, 76.8°

1901	TS	2
1903	H3	2
1909	TS	11
1910	H1	3
1915	H1	Galveston
1916	H2	4
1917	TS	3
1928	TS	3
1931	TS	6
1932	TS	7
1933	TS	3
1934	TS	10
1938	TS	2
1942	TS	4
1944	H3	4
1951	H1	Charlie
1974	TS	Carmen
1980	H4	Allen
1988	H3	Gilbert
1994	TS	Gordon
2001	TS	Iris
2004	H3	Ivan
2005	H1	Dennis

Montego Bay, Jamaica 18.5°, 77.9°

1901 TS 2
1903 H3 2
1904 TS 1
1910 H1 3
1912 H2 7
1915 H2 Galveston
1916 H2 4
1928 TS 3
1931 TS 6
1932 TS 7
1933 TS 3
1933 H2 19
1934 TS 10
1935 H1 4
1939 TS 5
1944 H1 4
1949 TS 11
1951 TS Charlie
1980 H4 Allen
1988 H3 Gilbert
2002 TS Lili
2004 TS Charley
2004 H4 Ivan
2005 H2 Emily

Negril, Jamaica 18.3°, 78.3°

1903 H3 2
1904 TS 1
1909 TS 8
1910 TS 3
1912 H3 7
1912 TS 7
1915 H2 Galveston
1916 H1 4
1928 TS 3
1931 TS 6
1932 TS 7
1933 TS 3
1933 H2 19
1935 H2 4
1938 TS 2
1944 H1 4
1947 TS 6
1948 TS 7
1949 TS 11
1951 H1 Charlie
1974 TS Carmen
1980 H2 Allen
1988 H3 Gilbert
2002 TS Isidore
2004 H4 Ivan
2005 H3 Emily

Ocho Rios, Jamaica 18.4°, 77.1°

1903	H3	2
1910	H1	3
1912	H1	7
1915	H2	Galveston
1916	H2	4
1924	TS	8
1931	TS	6
1932	TS	7
1933	TS	3
1933	TS	19
1934	TS	10
1935	TS	4
1944	H3	4
1949	TS	11
1951	H1	Charlie
1974	TS	Carmen
1980	H4	Allen
1988	H3	Gilbert
2001	TS	Iris
2004	TS	Charley
2004	H3	Ivan
2005	H1	Dennis
2005	TS	Emily

Fort-de-France, Martinique 14.4°, 61.1°

1901	TS	3
1903	H2	2
1916	H1	4
1918	TS	5
1919	TS	2
1921	TS	3
1924	TS	2
1926	TS	1
1931	TS	3
1931	TS	4
1941	TS	4
1942	TS	2
1942	TS	4
1948	TS	4
1951	H2	Dog
1960	H1	Abby
1963	H2	Edith
1964	TS	Cleo
1967	TS	Beulah
1970	TS	Dorothy
1979	H2	David
1980	H3	Allen
1988	TS	Gilbert
1989	TS	Hugo
1993	TS	Cindy
1994	TS	Debby
1995	TS	Marilyn
2004	TS	Ivan

San Juan, Puerto Rico 18.4°, 66.1°

1901 TS 7
1909 H1 6
1910 H2 3
1915 H2 Galveston
1916 H1 5
1916 TS 12
1926 H1 1
1928 H5 Lake Okeechobee
1930 H3 2
1931 TS 4
1931 H1 6
1932 H2 7
1933 TS 3
1933 TS 16
1938 TS 1
1942 TS 10
1945 TS 3
1956 H1 Betsy
1964 H2 Cleo
1966 H3 Inez
1967 H2 Beulah
1979 H3 David
1979 TS Frederic
1981 TS Gert
1984 TS Klaus
1989 H3 Hugo
1995 TS Marilyn
1996 H1 Hortense
1998 H2 Georges
1999 H3 Lenny
2004 TS Jeanne

Bassaterre, St. Kitts/Nevis 17.2°, 62.4°

1901 TS 7
1906 TS 4
1908 TS 1
1908 TS 8
1909 H1 6
1910 H1 3
1916 TS 2
1922 H1 2
1928 H4 Lake Okeechobee
1930 H1 2
1932 H1 7
1933 TS 3
1938 TS 1
1947 TS 9
1950 H1 Baker
1953 TS Edna
1956 TS Betsy
1959 TS Edith
1960 H4 Donna
1963 TS Helena
1964 H3 Cleo
1966 H2 Inez
1979 H2 David
1980 TS Allen
1989 H4 Hugo
1995 H2 Luis
1995 H1 Marilyn
1996 TS Bertha
1998 H3 Georges
1999 TS Lenny
2000 TS Debby

Castries, St. Lucia 14.0°, 61.0°

1901 TS 3
1903 H2 2
1916 H1 4
1918 TS 5
1919 TS 2
1921 TS 3
1924 TS 2
1931 TS 3
1931 TS 4
1941 TS 4
1942 TS 2
1942 TS 4
1943 TS 9
1948 TS 4
1949 TS 3
1960 H1 Abby
1963 H2 Edith
1964 H2 Cleo
1967 TS Beulah
1970 TS Dorothy
1979 H1 David
1980 H4 Allen
1988 TS Gilbert
1993 TS Cindy
1994 TS Debby
2004 TS Ivan

Marigot, St. Martin 18.4°, 63.5°

1901 TS 7
1906 H2 4
1908 H1 1
1908 TS 6
1910 TS 3
1916 H1 5
1916 TS 12
1922 H2 2
1924 H1 3
1926 TS Great Miami
1928 H3 Lake Okeechobee
1930 TS 2
1931 H2 6
1932 H3 7
1933 TS 5
1938 TS 1
1940 TS 3
1943 TS 2
1945 TS 9
1947 TS 9
1949 TS 2
1950 H2 Dog
1953 TS Edna
1955 TS Hilda
1960 H4 Donna
1964 H1 Cleo
1966 H1 Faith
1966 H2 Inez
1979 TS Claudette
1979 H1 David
1989 H3 Hugo
1990 TS Klaus
1996 H1 Bertha
1998 H1 Georges
1999 H1 Jose
1999 H3 Lenny
2000 H1 Debby
2004 H1 Frances

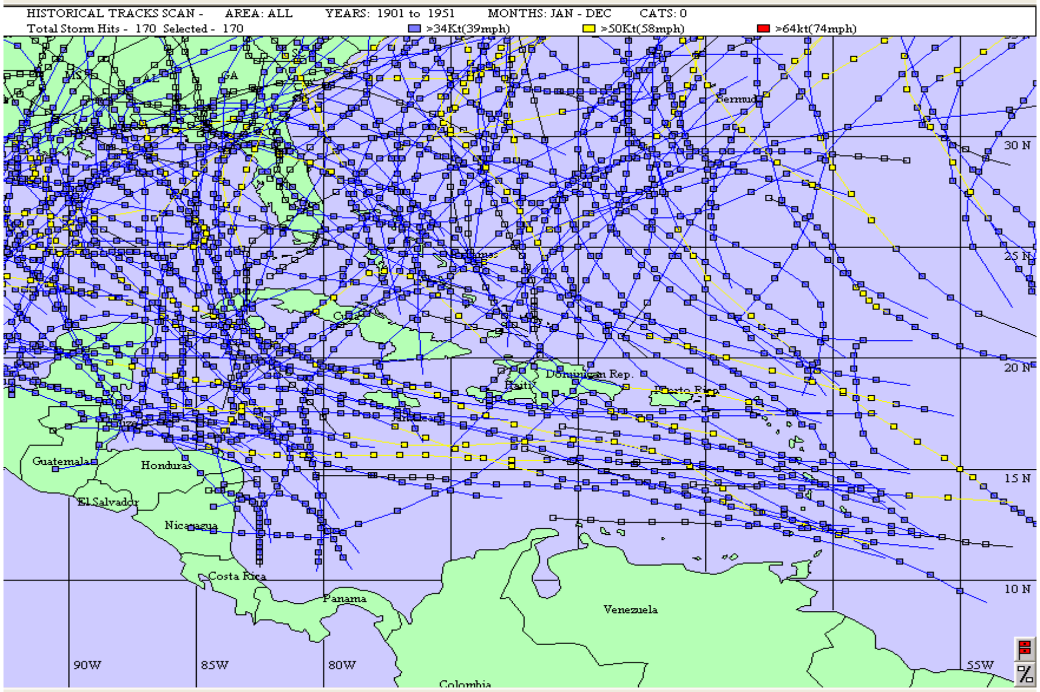
Charlotte Amalie, St. Thomas 18.2°, 65.0°

1901 TS 7
1906 TS 4
1908 TS 6
1909 TS 6
1910 H1 3
1916 TS 2
1916 H1 5
1916 H1 12
1922 H1 2
1924 TS 2
1926 TS 1
1928 H5 Lake Okeechobee
1930 TS 2
1931 TS 4
1931 H1 6
1932 H2 7
1933 TS 5
1938 TS 1
1940 TS 3
1942 TS 10
1949 TS 4
1956 TS Betsy
1960 H2 Donna
1964 H2 Cleo
1966 H2 Inez
1979 H3 David
1979 TS Frederic
1984 TS Klaus
1989 H3 Hugo
1995 H1 Luis
1995 H2 Marilyn
1996 H1 Bertha
1998 H2 Georges
1999 TS Jose
2000 H1 Debby

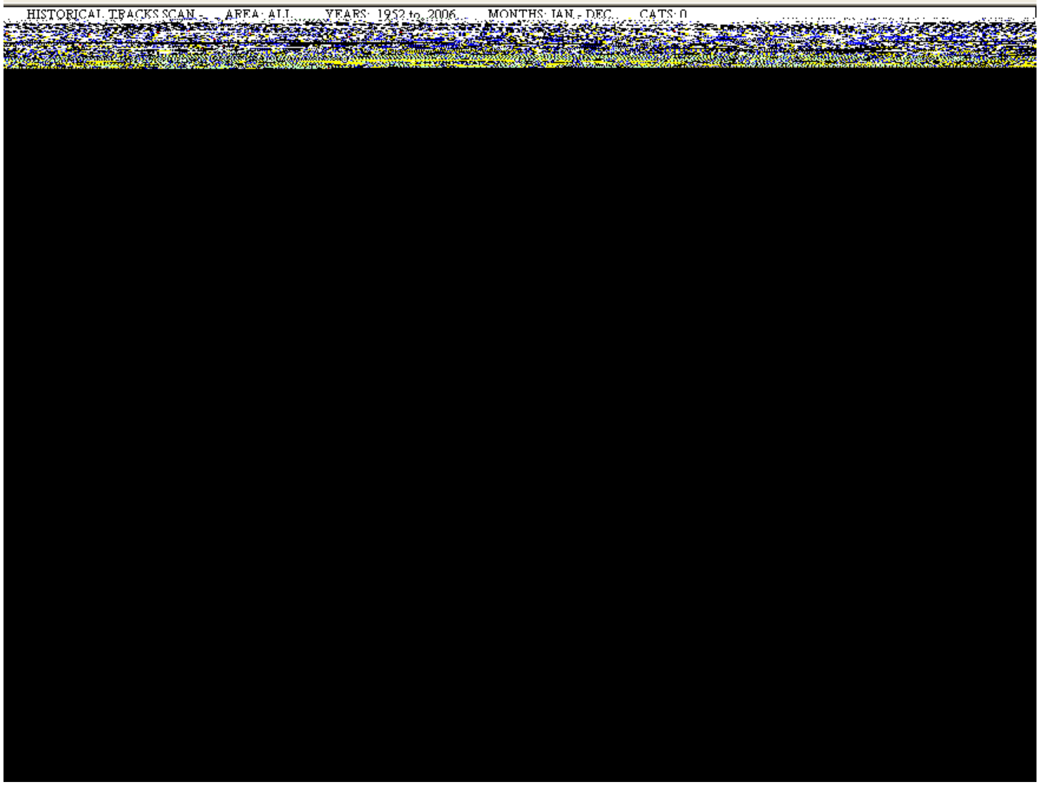
Grand Turk, Turks & Caicos 21.4°, 71.1°

1901 TS 3
1906 H4 4
1908 TS 6
1909 TS 11
1919 H1 2
1923 TS 2
1926 H2 1
1926 H4 Great Miami
1928 H4 Lake Okeechobee
1932 TS 3
1932 H1 4
1933 H1 5
1933 H1 11
1933 H2 12
1934 TS 11
1940 TS 1
1940 TS 3
1941 TS 6
1945 H3 9
1948 TS 1
1952 TS Charlie
1953 TS Dolly
1954 TS Edna
1956 H2 Betsy
1960 H3 Donna
1960 TS Florence
1963 TS Edith
1985 TS Isabel
1985 H1 Kate
1996 TS Bertha
1996 H2 Hortense
2003 TS Mindy
2004 H4 Frances

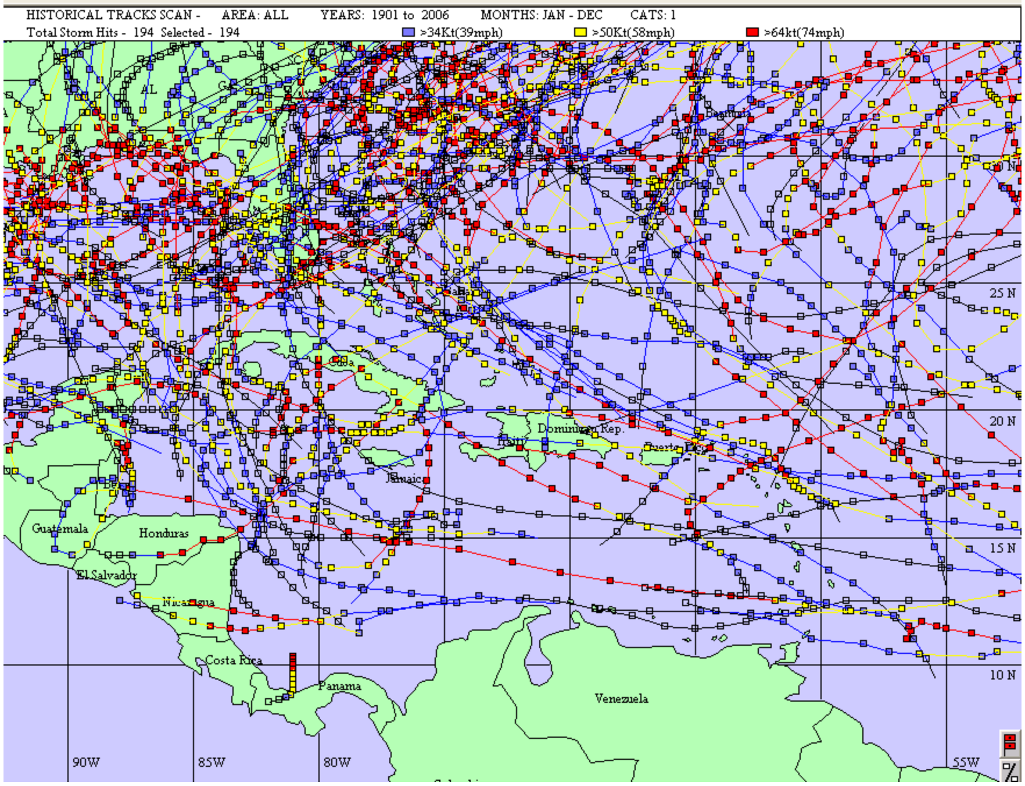
Appendix B: Storm Tracks in the Caribbean for the One Hundred Six Year Dataset (1901 through 2006)


HISTORICAL TRACKS SCAN - AREA: ALL YEARS: 1901 to 1951 MONTHS: JAN - DEC CATS: 0
Total Storm Hits - 170 Selected - 170

Tropical Storm Tracks: 1901 through 1951


HISTORICAL TRACKS SCAN - AREA: ALL YEARS: 1952 to 2006 MONTHS: JAN - DEC CATS: 0

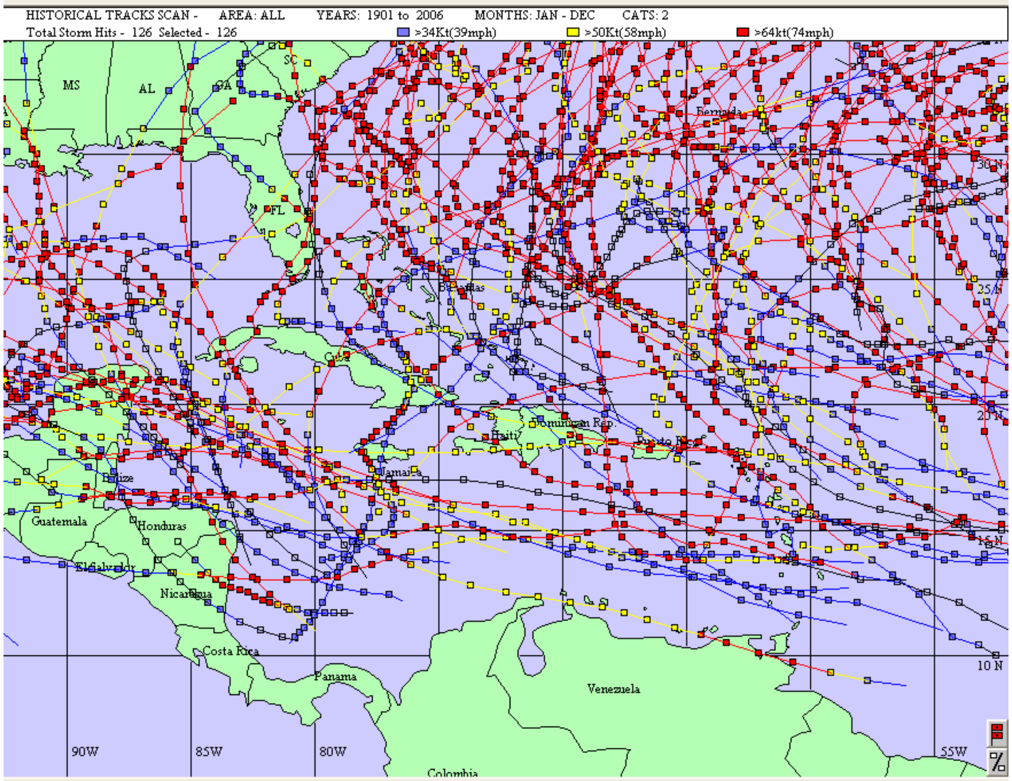
Tropical Storm Tracks: 1952 through 2006



HISTORICAL TRACKS SCAN - AREA: ALL YEARS: 1901 to 2006 MONTHS: JAN - DEC CATS: 1

Total Storm Hits - 194 Selected - 194 🟦 >34Kt(39mph) 🟨 >50Kt(58mph) 🟥 >64kt(74mph)

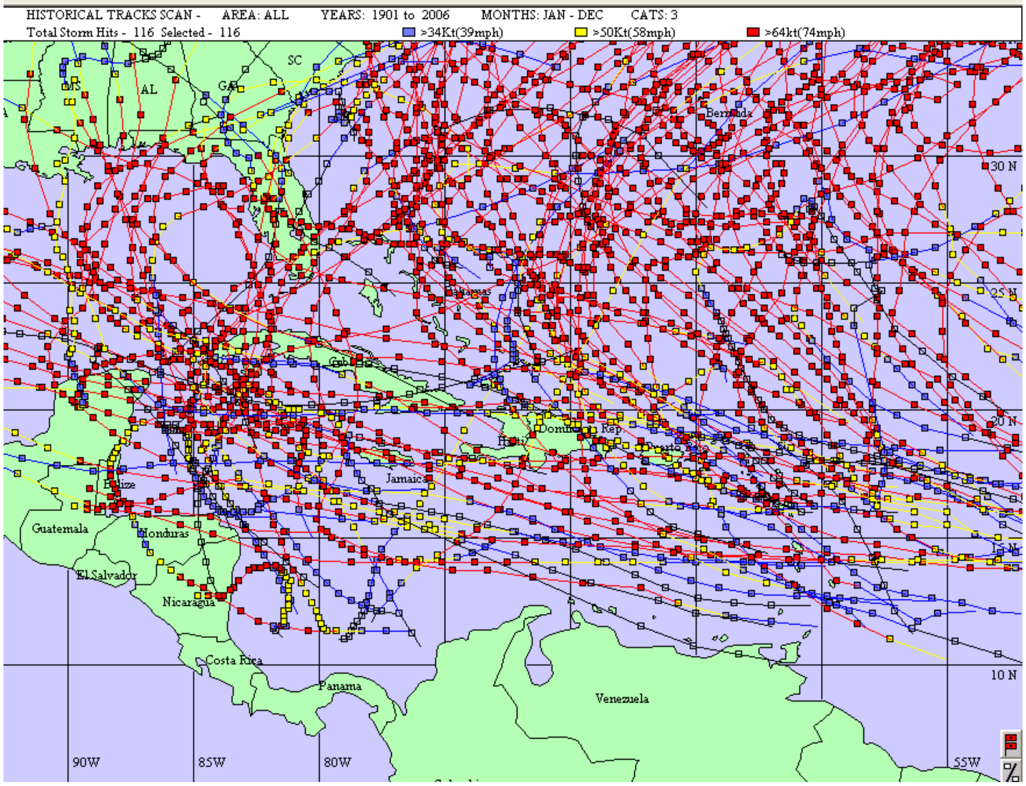
Category 1 Storm Tracks



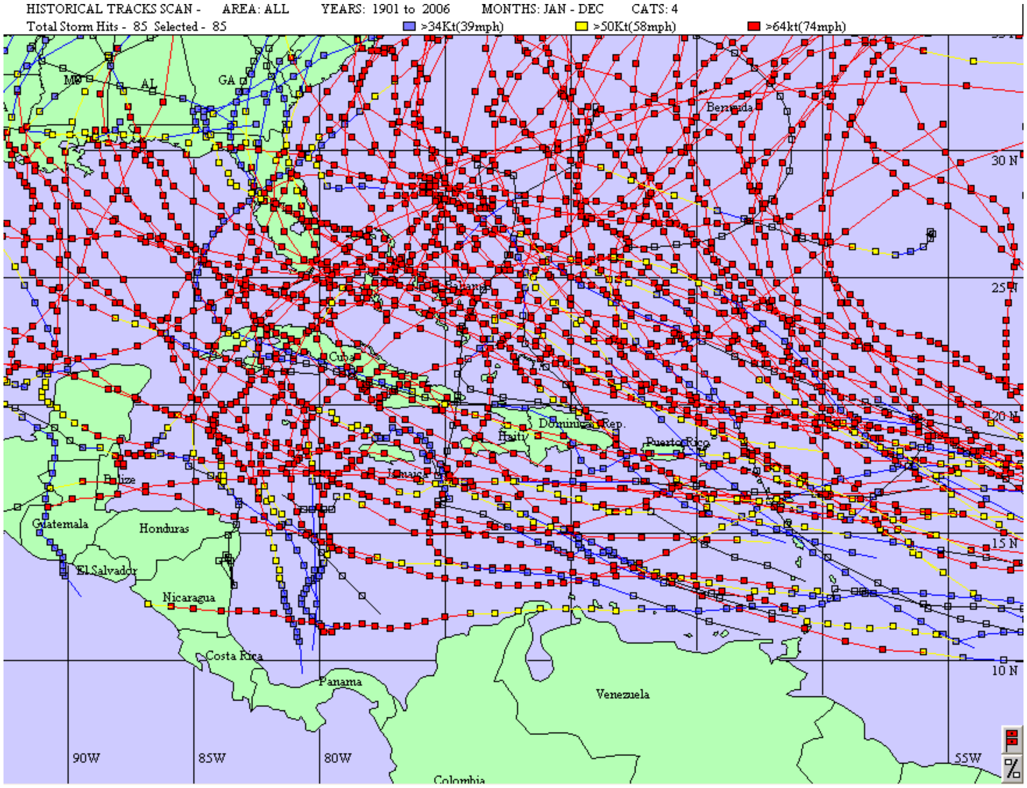
HISTORICAL TRACKS SCAN - AREA: ALL YEARS: 1901 to 2006 MONTHS: JAN - DEC CATS: 2

Total Storm Hits - 126 Selected - 126 🟦 >34Kt(39mph) 🟨 >50Kt(58mph) 🟥 >64kt(74mph)

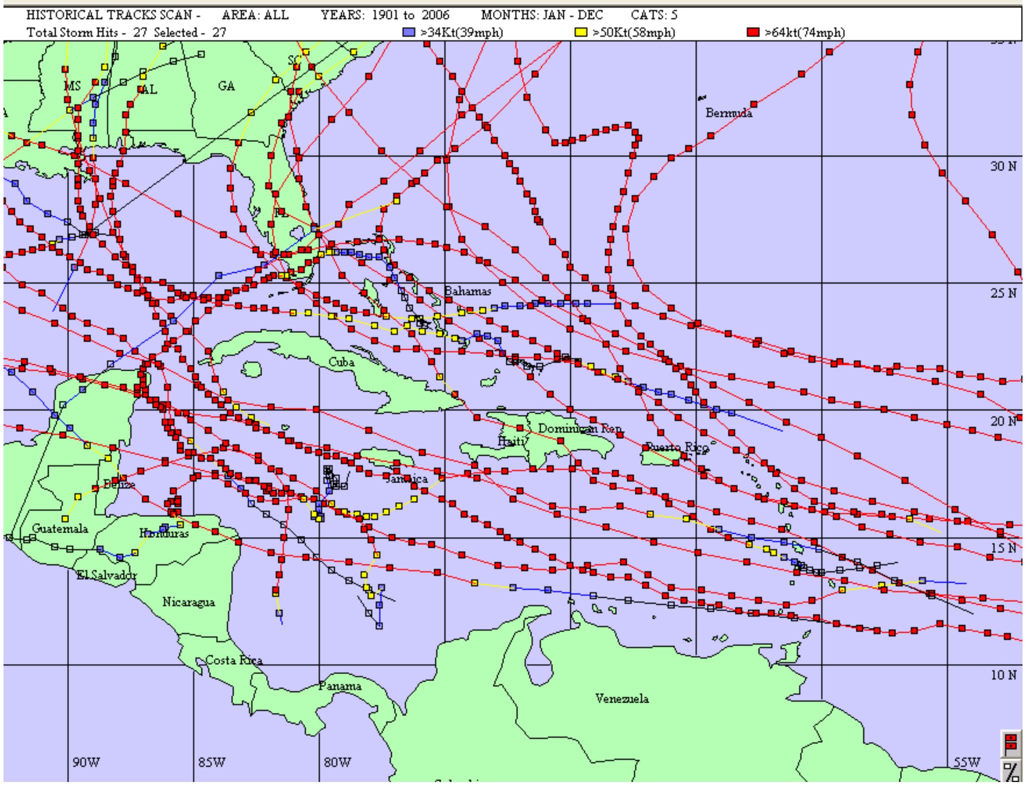
Category 2 Storm Tracks



Category 3 Storm Tracks



Category 4 Storm Tracks


HISTORICAL TRACKS SCAN - AREA: ALL YEARS: 1901 to 2006 MONTHS: JAN - DEC CATS: 5

Total Storm Hits - 27 Selected - 27

Category 5 Storm Tracks

Vita

Alexa (“Lexie”) Jo Andrews is a native of Baton Rouge. She began her studies at Louisiana State University in August of 2000 before earning her Bachelor of Science degree in geography in 2004. In 2005, Lexie began her pursuit of a Master of Science degree in geography with an emphasis in climatology. After graduation, she hopes to continue her career in the field of emergency management.