THE IMPACT OF TROPICAL CIRCULATION SYSTEMS ON THE CHESAPEAKE BAY REGION: A CLIMATOLOGY AND DAMAGE ASSESSMENT

by

Abigail Lisa Marie Ingram

A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Science in Geography

Fall 2012

THE IMPACT OF TROPICAL CIRCULATION SYSTEMS

ON THE CHESAPEAKE BAY REGION:

A CLIMATOLOGY

AND DAMAGE ASSESSMENT

by

Abigail Lisa Marie Ingram

Approved: ____
Daniel Leathers, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: ____
Tracy DeLiberty, Ph.D.
Chair of the Department of Geography

Approved: ____
Nancy M. Targett, Ph.D.
Dean of the College of Earth, Ocean, and Environment

Approved: ____
Charles G. Riordan, Ph.D.
Vice Provost for Graduate and Professional Education

ACKNOWLEDGMENTS

I would like to thank my advisor, Dan Leathers, for not giving up on me over these past years as I struggled to finish this thesis. He never once let me submit to my lack of confidence when it came to writing. I would also like to thank my husband, Robert Ingram Jr., for not getting angry with me for refusing to "get off the pot" so many times. My mom, my cheerleader, Karen Buck, has been a constant support in and always encouraged me and supported whatever path I decided to take in life. My grandfather, John Hall Sr., has always believed in me and will always be my hero. "This is for you, Pop-pop!". I would be remiss if I did not mention my best friend, Julya, for getting my butt in gear and insisting that I get this damn thing done! Finally, I wanted to thank my son, Elias, who is not born yet, for giving me the inspiration to keep plugging away during the final stretch. I didn't want to let him down.

TABLE OF CONTENTS

Appendix

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The record of tropical circulation systems (TCS) affecting the Chesapeake Bay Region (CBR) extends back into the 16th century, with a more detailed record beginning in 1950 that includes damage estimates for each storm. Between 1950 and 2006, the CBR accrued a total of $4,158,431,635 ($14,642,055,086 in 2011 USD equivalency) in damages resulting from TCSs. This region is ecologically sensitive but also sensitive in terms of the built environment and the damages that result from passing TCSs. A climatology of TCSs affecting the region is constructed providing information on the origin, path, intensity, and seasonality and each with a series of sub-types. The damage types defined in the TCS climatology include flooding, high winds, storm surge, and other (which includes any complicating factors such as tornadoes). Using the data collected between 1950 and 2006, a damage database is created to classify and quantify the climatological factors and damage types resulting from each storm. From this database, the costs associated with specific climatological factors and each damage type is determined. Of the climatological factors, the damage results vary greatly between the total cost of each sub-type and the cost per event for each sub-type. Using category as an example, the highest total cost is accrued by tropical storms ($2,565,954,210), whereas; the most costly per category cost is for category 1 TCSs ($202,631,100). While this study did not find a significant trend in damage amounts over time, the most costly of the damage types is flooding, causing a total of $2,889,944,884 ($11,535,539,477 in 2011 USD equivalency). The results provide a generalized representation of the effects and damages for this region, and

will allow proper preparation and mitigation for tropical circulation systems. The damage database created can be applied to other areas that tropical circulation systems affect and used as a tool to inform the public on these important coastal hazards.

Chapter 1

INTRODUCTION

Tropical Circulation Systems (TCS) such as hurricanes and tropical storms play a role in defining the climate of the Mid-Atlantic Region of the United States, which includes the Chesapeake Bay Region (CBR). Economically, these powerful and destructive systems are also responsible for causing collectively billions of dollars in damages along US coastal zones in the recent past (Landsea 1993). The historical record of hurricanes extends back into the 16th century, documented by explorers and traders of their time tracking tropical storms in the ship's log. There are also many eyewitness accounts that have been found in old newspapers as well as personal letters and diaries. Due to the level of technology of the time, these early records read in a narrative fashion and are without the degree of detail that is available today, yet they still document early tropical systems. An example of these early accounts is found in David Ludlam's *Early American Hurricanes* (1963). There are three Chesapeake specific TCSs mentioned in the book with a notable excerpt for this region being from Norfolk's Virginia Gazette (1 October 1785) reporting on the Equinoctial Storm of 23-24 September 1785:

> "A higher tide level and severer storm were never known than happened in this place yesterday; the damages sustained thereby are immense—almost all of the ships in the harbor were drove from their moorings, and many warehouses were entirely carried away—vast quantities of salt, sugar, corn, lumber and other merchandise were totally lost—the lower stores of many dwellings were filled with water".

Another in a letter published in Norfolk's Independent Gazette (8 August 1788) of George Washington's Hurricane on 23-24 July 1788:

> "Wednesday last (23rd) the most violent storm ever known commenced for 9 hours- wind at start from NE- at 0030 it suddenly shifted to S and blew a perfect hurricane—tearing up large trees by the roots, removing houses, throwing down chimneys, fences, etc, and laying the greatest part of the corn level. The tide was not so high as in 1785 [referring to The Great Gust of 1785, also documented in this book]. Only two ships in Hampton Roads survived the gale."

These records do give some monetary detail as far as damages are concerned, but more importantly they act as confirmation that tropical systems have in fact been passing through this region for centuries. Using these early accounts of TCS activity along with the storm and damage data available today, a climatology of TCSs can be formed for this region.

Beginning in the mid-nineteenth century, hurricane records began to document information regarding the intensity and position of storms at six-hour time intervals. This method allows for the evaluation of the storm's unique storm track. In 1950, hurricane damage data became available along with a more detailed and precise hurricane record. Combined, these data provide a powerful tool with which to conduct damage surveys and begin to estimate and analyze damage trends. The damages that result from tropical systems vary along with the strength of the storm, but these systems are also a function of other natural and human factors including: the overall ecological vulnerability of the area, geography, population and infrastructure. The historical damage record shows that damages directly affecting people increase with time. As areas become populated and developed there is simply more for tropical systems to destroy. Population increase in the United States has historically been greatest along the coasts (Crossett 2004), precisely where hurricanes make their landfall. In 2010, the Chesapeake Bay watershed had an estimated population of 17.2 million people, a 5.2 percent increase in the previous six years. It is projected that by the year 2030 the population will exceed 20 million people (Chesapeake Bay Program, 2012).

As one of the country's most important ecosystems, the vulnerability and overall health of the Chesapeake Bay is the main focus of many research studies and articles and has been explored from many different perspectives. The Chesapeake Bay is the largest estuary in the United States with a watershed of approximately 165,760 km^2 (64,000 mi^2) enveloping portions of New York, Pennsylvania, Virginia and West Virginia, Delaware and Maryland. The bay holds an average of 18 trillion gallons of water, but overall is surprisingly shallow because much of it is made up of marshes and tidal wetlands. The average depth of the Bay is 6.4 meters (21 ft.) with a maximum depth of around 53 meters (174 ft.). With about 18,804 km (11,684 mi) of shoreline, the passage of a TCS has much to disrupt especially in terms of coastal damage (Chesapeake Bay Program, 2012). From an ecological standpoint, the fact that the Bay is an estuary (where salt and fresh water mix) means that the delicate estuarine balance is easily disturbed by a TCS. The biota of the Bay depends on a certain level of salinity and turbidity, which are modified when a TCS moves through. With the passage of a TCS, the salinity decreases with the large amount of rainfall and inflow of fresh water from its tributaries. The waters become littered with debris runoff from the land surface. Any one of these events can harm the ecological balance, disrupting the equilibrium of the system too quickly for the flora and fauna to adapt. Depending upon the magnitude of the TCS, and how well the ecosystem can equilibrate, the economy of the CBR can be greatly impacted. The economy can face severe loss if the seafood and recreation industries of the CBR are severely affected. This scenario was evident after Isabel in 2003, a Category 2 hurricane that moved through the region. Weeks after the storm the Bay experienced the largest algae bloom in nearly twenty years caused by the sharp increase of nutrient levels due to severe land-surface flooding. This algae causes the 3,600 species of Bay life (flora and fauna) to suffer with two-fold effects. First, the algae block out any sunlight from reaching aquatic plant life causing them to die, and secondly the decomposition of the plants and dead algae use up dissolved oxygen in the water. This process is known as anoxia. (Miller, et al. 2006) Beyond the ecological effects of a TCS, the very same dynamics can cause tremendous amounts of erosion throughout the entire region, again affecting the economy.

This study constructs a basic TCS climatology for the CBR using records dating back to 1851, and then in further detail investigates the type and cost of damages in the CBR resulting from storms that passed through or near the region between 1950 and 2006. The analysis of the damages involved a combination of investigating the climatological characteristics of each storm using geographic information systems (GIS) and examining the damage data in US Dollar amounts using tabulated data sources. Using GIS, each storm that affected the region was plotted and organized according to origin, intensity, intensity, timing (month of occurrence) and path in order to get an overall view of hurricane activity in the CBR over time. This information was combined with damage data (type and cost) to evaluate the financial effects that people in the region face in the wake of a TCS.

Chapter 2

LITERATURE REVIEW

The Chesapeake Bay and its vicinity is the subject of numerous studies. These studies range from the physical properties of the bay water to various studies regarding bay wellness and ecology. Likewise, tropical circulation systems that impact the Atlantic basin have been studied extensively. However, the damages caused by TCSs in the CBR have never been studied in a comprehensive manner. Three main categories of articles and scholarly papers related to the CBR's relationship to TCSs can be found. First, there are general articles regarding tropical circulation systems, in this case, those that occur in the North Atlantic basin. The second category contains articles based specifically on the Chesapeake Bay and its climatological and ecological history. Finally, the third category focuses on damages resulting from hurricanes and how they have been examined in other areas across the United States. As previously stated, the vast majority of scholarly papers regarding the Chesapeake Bay are written on ecological aspects of the Bay. While these topics are important to examine, the focus of this study is monetary damages, as well as injuries and fatalities associated with TCSs in this region.

2.1 North Atlantic Tropical Circulation Systems

The frequency and magnitude of hurricanes in the North Atlantic is a highly researched topic. The subject of climate change is on the mind of many scientists who have related this apparent warming to hurricane frequency and magnitude. Zhang, et al. (2000) found that there is a definite variation in hurricane frequency and magnitude seen throughout the last century, but no sign of an overall intensification of these systems. Their claim is that the storms experienced now are the same severity as were experienced a century ago, but with the current high levels of coastal development and sea level rise, the experiences seem more severe. Spatially, Elsner, et al. (2000) examine the factors that determine the path and frequency of TCSs and where they eventually make landfall. Hurricane path is closely linked to the North Atlantic Oscillation (NAO) with positive (negative) stages of the oscillation having high (low) latitude recurving (non-recurving) paths. The NAO can affect the path and point-of-impact of a TCS as it passes through the CBR. TCSs with a positive or recurving path are more likely to make landfall along the coast of the CBR, whereas TCSs during negative or non-recurving phases take a more southerly path before reaching the CBR as they make landfall at lower latitudes. The frequency of hurricanes is found to be dependent on the El Nino Southern Oscillation (ENSO). During El Nino, there are fewer hurricanes in the Atlantic Basin due to increased wind shear that prevents development, however during La Nina hurricanes are more frequent in the Atlantic Basin due to lack of wind shear. Along those same lines, Keim, et al. (2004) state that the overall frequency of extratropical systems has decreased, but the frequency of intense systems has increased. They also link the longitude of origin to the latitude of impact. Hurricanes formed in the east (west) Atlantic are more likely to make landfall at high (low) latitudes along the east coast of the U.S. Further, Landsea (1993) came to the same conclusion adding that the most intense hurricanes of the season occur between the months of August and October and begin as easterly waves off the coast of Africa. Also, these intense systems may be induced by the “differential warming pattern” found between the surface water of the Atlantic and the lower troposphere (Balling and Cerveny 2006). They noted that the lower tropospheric temperature is not warming along with the water surface temperature acting as an incentive for hurricane development.

2.2 Climate Change Across The Chesapeake Bay Region

In terms of recent climatic anomalies, the sediments of the Chesapeake Bay provide an excellent source of paleoclimate data that aid in extending the Holocene climate record (Cronin et al., 2000). Sediment cores have been very helpful in identifying the temperature fluctuations of the Medieval Warm Period and the Little Ice Age as well as larger scale climate cycles in the bay region (Cronin, et al. 2003). These same sediment cores have been used to identify precipitation cycles for the entire mid-Atlantic region. More specifically, the temperature of the bay water is under examination as to whether or not it has varied significantly over time (Cronin, et al. 2000). Preston (2004) found that bay surface temperatures did in fact increase by 0.8ºC and the subsurface by 1.1ºC over the past fifty years. This temperature increase correlated with Atlantic Ocean temperature cycles, but may also involve human factors. Similarly, Brady (2006) suggests that there is an apparent warming of the bay’s temperature, but the results should be approached with caution until the temperature record (buoy data) can be extended over a longer period of time. There are several examples of Chesapeake Bay research that explore the way in which the bay water physically responds to the passing of a storm. Shen, et al. (2006a) performed a tide and storm surge analysis using tide gauge data and a tide simulation model on the affects of Hurricane Floyd in 1999. After Hurricane Floyd's passing, two distinct high peaks in water level occurred in the lower bay, but they were not apparent at more northern locations. They find that the two dominant factors that determine bay storm-tide are offshore storm tides and local wind forcing. Offshore storm tides influence the lower bay water levels, while local winds have more influence in the upper bay region water levels. The same authors (2006b) find similar results when applying an UnTRIM structure grid model to Hurricane Isabel in 2003. Again, the upper bay regions are affected primarily by local winds whereas the lower bay is affected by the offshore storm-tide. Li, et al. (2006) take into account the geometry and orientation of the bay in regards to a passing hurricane, in this case using Isabel (2003) as a case study example. The waves within the bay tend to favor a north/south elongation rather than east-west, reflecting the shape of the bay. The authors also examine the destratification in the water column caused by the waves' mixing and how it results in hypoxic (oxygen depleted) water unsuitable for bay life.

2.3 TCS Damage

Pielke and Landsea (1999) correlate Eastern U.S. hurricane damage to the ENSO cycle. They find that there is an increase in overall damage loss during periods of La Nina and a reduced damage loss during El Nino. During La Nina events, the frequency of Atlantic storms increases, but also the strength of and damage resulting from each storm increases. Specifically, La Nina years had a "77% probability of incurring at least $1 billion in damages, compared to El Nino years' 48% probability." This suggests that an increased level of alertness and preparedness should take place when a La Nina phase of the ENSO is forecast. In addition to the onset of a La Nina phase, Saunders and Lea (2005) use wind anomalies to aid the prediction of a landfalling hurricane as well as the damage potential of the hurricane. They identify 6 (six) regions of 925-400 mb July wind anomalies in the Northern

Hemisphere that favor or diminish hurricane genesis and evolution. The hindcast model that they created showed a very clear link between the U.S. Accumulated Cyclone Energy (ACE) index and the amount of economic and insured losses that were accrued each year. They also state that "had the acting insurance agencies during the 2004 hurricane season referred to the U.S. ACE index forecast used in the study, they would have reduced their losses" (Saunders and Lea, 2005, 1007). Estimating hurricane loss is also the goal of Watson and Johnson (2004) who compares 324 combinations of models to actual accrued losses in order to examine the effectiveness of each model in determining hurricane damages. Out of the total 324 models examined, the top four could be singled out as best predictors. Each model had similar outputs per storm, but each storm is distinct in the detailed characteristics such as Opal's "rapid collapse upon landfall" and Floyd's "unusual flooding". Each of these deviations from an average hurricane can affect the loss amount. It is this discrepancy between models that cause insurers and officials the most trouble when trying to determine how much they should pay out in damages. Watson and Johnson (2004) suggest that the current models used in hurricane damage loss estimation need significant improvement in order to appease insurance and governmental agencies. Until the creation of a more precise damage model, insurance agencies will continue to use proprietary models to determine pay-outs.

Pielke and Landsea (1998) express that the apparent increase of U.S. hurricane damages between 1925 and 1995 is misleading when you account for economic influence such as inflation and societal changes such as wealth and population increase over time. When the damage amounts over the years are normalized to 1995 dollars, the apparent increase is not pronounced. With climate change on the mind of the government and people of the U.S. it is easy to blame the increase in hurricane damage costs on global warming, whereas these authors remove any economic bias to view the damage amounts on an even playing field. The normalized dataset does show some variability, but it is in the sheer number of hurricanes that cause respective damage. In terms of actual damage estimate analysis, Downton and Pielke (2005) evaluate the accuracy of damage loss data in terms of flood damage. In the aftermath of a disaster event (a flood, hurricane, etc.) the situation itself proves to be an obstacle in collecting accurate damage estimates. The authors find that the longer the event and larger the effected area, the more accurate the estimate, while the smaller the effected area, the more inaccurate the estimates are. In addition to these sources of inaccuracy, the authors find that areas experiencing moderate levels of damage are often unaccounted for and cause an underestimation in damage loss. All of these factors cause the overall damage estimate to be inaccurate, either over or underestimating true damage amount. In terms of flood damages, Downton and Pielke (2005) suggest several realistic and uncomplicated ways to increase the accuracy of damage estimates.

A new post-landfall classification system proposed by Senkbeil and Sheridan (2006) better describes the actual "felt" damages post-landfall. The Saffir-Simpson scale (SS-scale) has its strength in pre-landfall periods, but after the hurricane makes contact with land and damages begin to accrue, a different classification system would be helpful and relevant to the average citizen. The proposed system includes 6 (six) types of damages: open water storm surge, duration of hurricane force winds, maximum sustained winds, gust score, minimum central pressure and rainfall. Each storm has a cumulative score of 100 and each type category is assigned a score 1-100. This post-landfall classification system can account for more of the characteristics of a hurricane that cause damage, not just the wind speed as relayed by the SS-scale.

Chapter 3

DATA AND METHODS

The tropical system stormtrack data are collected from NOAA's 'Historical Hurricane Track' generator that produces stormtracks in a line (vector) format compatible with a GIS (NOAA, 2012). The generator pulls selected information from NOAA's International Best Track Archive for Climate Stewardship (IBTrACS) data set (see the 'Help' menu at the aforementioned website). The initial data set includes all of the tropical systems in the Atlantic Basin that occurred from 1851 to 2005. Storms that occurred in 2006 were added manually to the data set at a later time and are not represented in the maps. Each individual track represents 6-hour time-step measurements that record a tropical system's location (latitude and longitude of the storm), pressure (in millibars), wind speed (in knots) and the category of the storm (using the Saffir Simpson Scale, Appendix A) at each point in time. The majority of the earlier storms, those prior to 1950, do not have pressure readings, but only wind speed and category that range from tropical depression to category 3 hurricanes.

3.1 Defining the Study Region

The Chesapeake Bay Region (CBR) is defined by creating a latitude /longitude 'box' extending from 74° to 78° West and 37° to 40° North. This box encloses the area surrounding the main body of the Chesapeake Bay (see Figure 3.1). The purpose of defining such a box is to use it as a selection device in a GIS and would determine if a tropical storm would be included in the CBR dataset or not. The size of the box is large enough to "capture" all of the tropical storms that may have had an impact on the region and eliminate those storms that do not. Simply stated, any storm that passes through this defined study area would be more likely to affect the region than a storm passing outside of the box. Using a well-known case as an example, Katrina, a storm that passed through the Gulf of Mexico making landfall in Louisiana, was too far away from the CBR to cause damage and would not be included in the CBR dataset. This creates a succinct set of storm tracks to perform a climatology and damage assessment upon.

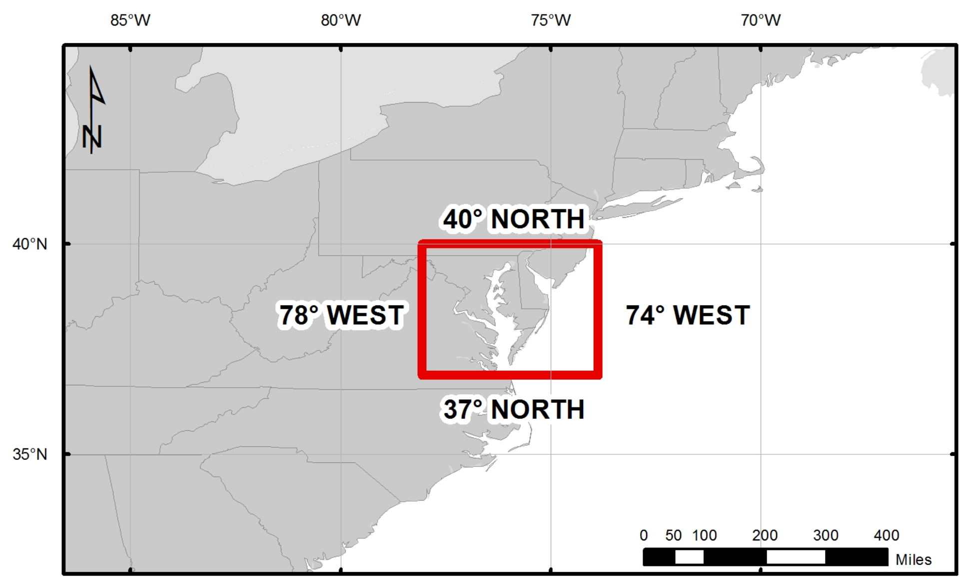


Figure 3.1: Boundaries for the Chesapeake Bay Region

The CBR Tropical Circulation System Database (CBR-TCS Database) includes all of the tropical systems with any part of their track falling within or touching the boundaries of the 'box'. Tracks are chosen manually using the select tool in ESRI Desktop ArcGIS. A geographic latitude/longitude coordinate system is used along with the 1983 North American Datum (NAD83) to create a series of storm track maps. These maps are used for display purposes only, so a specific projection is not necessary as distortion is of minimal concern. Out of the 1357 total systems in the Atlantic Basin dataset between 1851 and 2006, only 118 of them impact the region directly and form the basic TCS climatology stormtrack dataset. Once the storms are selected, they become the Chesapeake Bay Region Tropical Circulation System Database used in this study. Out of the 118 storms, 50 of them are evaluated in the damage assessment. The assessment includes storm data collected beginning in 1950 when more accurate technology and recording methods came into use. The data collected in this timeframe provides more variables to examine.

The TCS Database consists of both a graphical representation of each storm as it passes through the CBR, and a tabular form listing the attributes associated with each system in the form of shapefiles and associated attribute tables. The attribute table includes a tropical system's name, year, month, day, time, latitude, wind speed, pressure and intensity when it passed through the CBR. The reading at the initial time-step of each TCS as it crosses the study area boundary is used to represent the TCS in the database. This way each system has only one unique set of attributes used for analysis.

3.2 Damage Data

During the 1950's, The National Weather Service (NWS) began keeping record of all weather-related events that occur in the United States and US Territories along with any consequential damages reported. The National Climatic Data Center (NCDC), an affiliate of NWS and NOAA, has an online searchable Storm Events database (NWS-SED) (NCDC, 2012). As mentioned earlier, the initial damage reports read in a narrative fashion written on a year-to-year basis. In order to find the data relevant to the this study, the researcher must read through the entire year to find appropriate data. The method of data recording (in the NWS-SED) eventually evolved into a more comprehensive format that combined narrative weather data with tabular information. The more recent NWS-SED is organized by state and county, then by the precise date(s) (year, month and day) of each weather event making for a more efficient search process. Also included are the effects of the event as well as damage estimates in US Dollars in an incremental manner (see Appendix B, NWS-SED Damage Cost Table). One deficiency is that damage amounts in the NWS-SED are initial estimates. When the damages are entered into the NWS-SED, they represent the initial cost estimates of the storm damages. In reality, it can take several months to determine the exact amount of damage, and damages to personal property are often not reported immediately. In some circumstances, the database gives specific accounts of incidents during and after the storm that illustrate the level of disorder (or lack of disorder) felt during the event. It is important to note that the NWS-SED does not always state whether the event was a TCS or not. Often the NWS-SED reports effects such as flooding or storm surge as the event, not the storm that caused it.

3.3 Creating the Damage Database

This thesis focuses on the damages that are a result of the passing of tropical circulation systems in the Chesapeake Bay Region. This involves a thorough review of the entire NWS-SED, a laborious task. Using the previously generated GIS data as the starting point and initial search criterion, the location and dates of all relative TCSs are obtained. First, Maryland, eastern Virginia, southern Pennsylvania and western Delaware are selected from the entire US NWS-SED. Then from this set of records, the date of the TCS event is used to further specify the data. As mentioned earlier, in a few cases TCS events are not mentioned specifically in the NWS-SED, but the effects (flooding or storm surge) and related damages are reported. To avoid missing a damage estimate and creating a blank damage report, rather than searching for a term specific to TCS (such as a tropical storm's name or simply the term 'tropical storm'), the date is always used in the search. The applicable TCS damage reports are then selected and organized creating the CBR Storm Damage Database (CBR-SDD) using a Microsoft Excel spreadsheet. The first set of column headers in the CBR-SDD document each TCS's unique characteristics including: name, year, BTID, month, day, intensity, origin, path, counties affected, death toll, injury toll, and damage amount. The second set of columns contain damage data: storm surge, flooding, wind, other, no report, and overall damage type. There is also a column for any additional notes or information that is helpful or interesting in regards to the TCS.

Most of the column headers in the database are self-explanatory, but several of them need additional explanation. The BTID (Best Track Identification) is a unique number assigned to each storm by NOAA. The attributes of origin and path are results of the analysis of this work and explained in the Climatology section (Chapter 4) of this thesis. The "counties affected" lists the counties in the CBR that declared any damages after a TCS event. The death toll and injury toll are the counts of deaths or injuries noted. The damage data contains each TCS's damage type value assignment for each category. The damage type value assignment scheme is explained below.

The damage amounts in the CBR-SDD are US Dollar amounts in $500 increments unless a specific amount was given in the damage data text. These amounts are the averages of the NWS-SED set damage amount ranges given for each event (see Appendix B for NWS-SED Damage Cost Table). For example, an NWS damage amount rank of 3 represents $500 to $5,000. So the amount used to represent the TCS damage in the CBR-SDD is $2,750. This is because working with only one value per event makes it easier to work with the dataset as well as emphasize individual event identities. Another problem encountered in the search involves the early narrative damage records. In some instances in the NWS-SED, a damage estimate is given to represent a large area, but only a portion of the area falls within the boundaries of the CBR. In these cases, the cost of damage used to represent the CBR and the percentage of the total area falling within the CBR limits are proportional. For example, if the NWS-SED reported that a certain TCS caused $1,000,000 in damages from North Carolina to Maryland, and approximately 30% of the area falls within the boundaries of the CBR, then 30% of the damage, or $300,000, becomes the amount entered in the CBR-SDD.

After reading each of the NWS-SED accounts, Damage Types specific to the CBR became evident. The specific damage types revealed in this thesis are: flooding, high winds, storm surge, other, and no report (in cases when no significant damage was reported after a storm). Tropical Circulation Systems are complex weather events and are likely to show evidence of two or more damage types in varying degrees. A major objective of this research is to define each storm by their most important damage type. In the CBR-SDD each storm has a column representing each damage type. Based on a qualitative assessment of the NWS-SED narrative, each damage type is assigned a number between 1 and 100 depending on the degree of influence that damage type has on the overall damage assessment. This system is used because it can also represent the percentage value of the total cost of damage based on the NWS-SED narrative. This way, any specific damage type will stand out if it has a higher degree of impact, and thus define the damages from a specific TCS.

Chapter 4

CLIMATOLOGY

Certain key climatological parameters regarding tropical circulation systems affecting the CBR were documented and require definition including: origin, path, storm intensity, and seasonality. These parameters are important to identify in order to form a climatology for the Chesapeake Bay Region. The maps shown in this climatology depict all of the TCSs occurring between 1851 and 2006, however the storm counts and respective tables used represent the 1950-2006 time period in effort to be consistent with the damage assessment (Chapter 5).

4.1 Origin

First, the origin of the storm is the point at which the storm was generated for each storm track. The four major origins of hurricane genesis recognized for systems that affect the CBR (along with their respective abbreviations used in the database) are: (1) Cape Verde (CV), (2) Caribbean (CARI), (3) Gulf of Mexico (GULF) and (4) the East Coast of the US (EAST) (see Figure 4.1). Typically, there are three major regions of hurricane genesis defined in climate studies (Cape Verde, Gulf of Mexico and Caribbean), but this study establishes the fourth point of origin of East Coast storms.

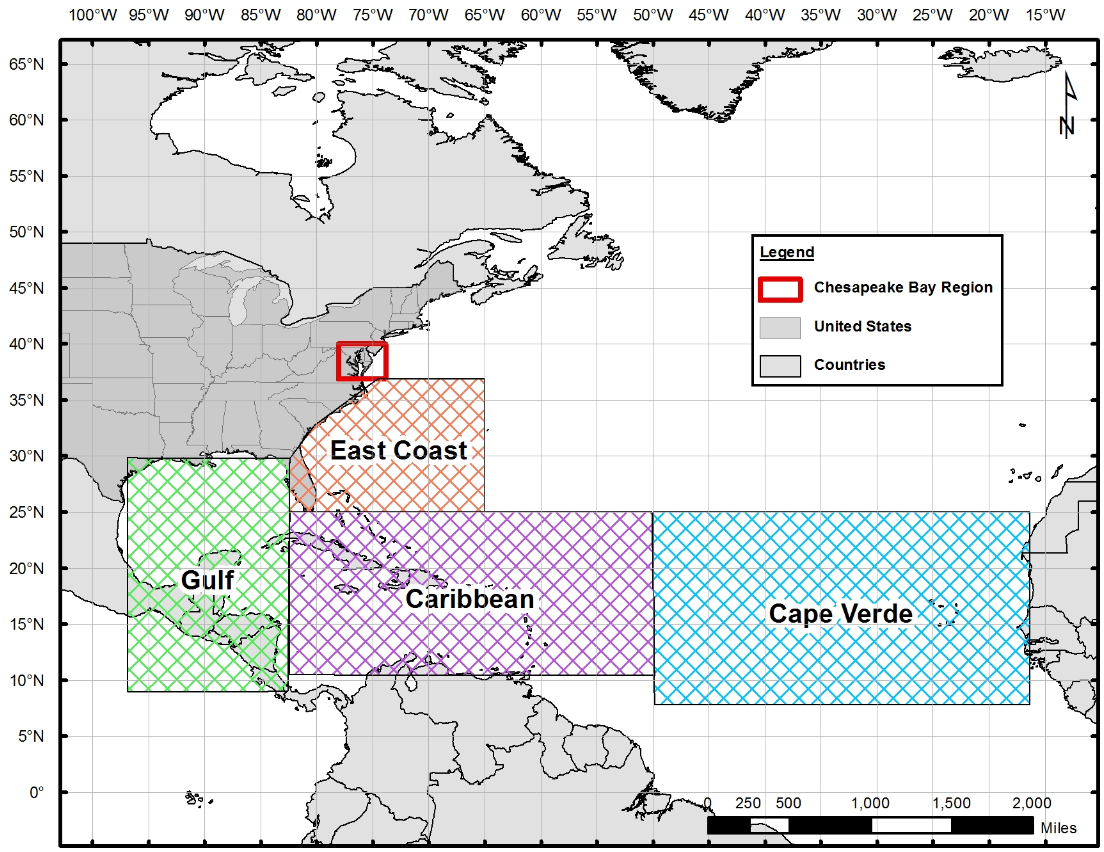


Figure 4.1: General TCS Origin Areas Defined in This Study.

Cape Verde storms originate on the West Coast of Africa and propagate westward across the Atlantic Ocean, specifically originating east of 50°W longitude. Caribbean storms originate in the Caribbean Sea, between the longitudes of 80.5°W and 50°W and south of the 25°N parallel. Gulf of Mexico storms originate in the area of the Gulf of Mexico, west of 80.5°W longitude. Finally, East Coast storms originate north of the Caribbean region, north of the 25°N parallel. This fourth origin area was added because there were a number of storms that were Caribbean in nature, but far enough removed to the north of the Caribbean origin area that they necessitated an additional category. (See Table 4.1 and Figures 4.2 – 4.5)

Table 4.1: Origin of TCSs in CBR 1950-2006.

ORIGIN LOCATION	COUNT
CAPE VERDE (CV)	13
CARRIBBEAN (CARI)	12
GULF OF MEXICO (GULF)	14
EAST COAST (EAST)	11
TOTAL	50

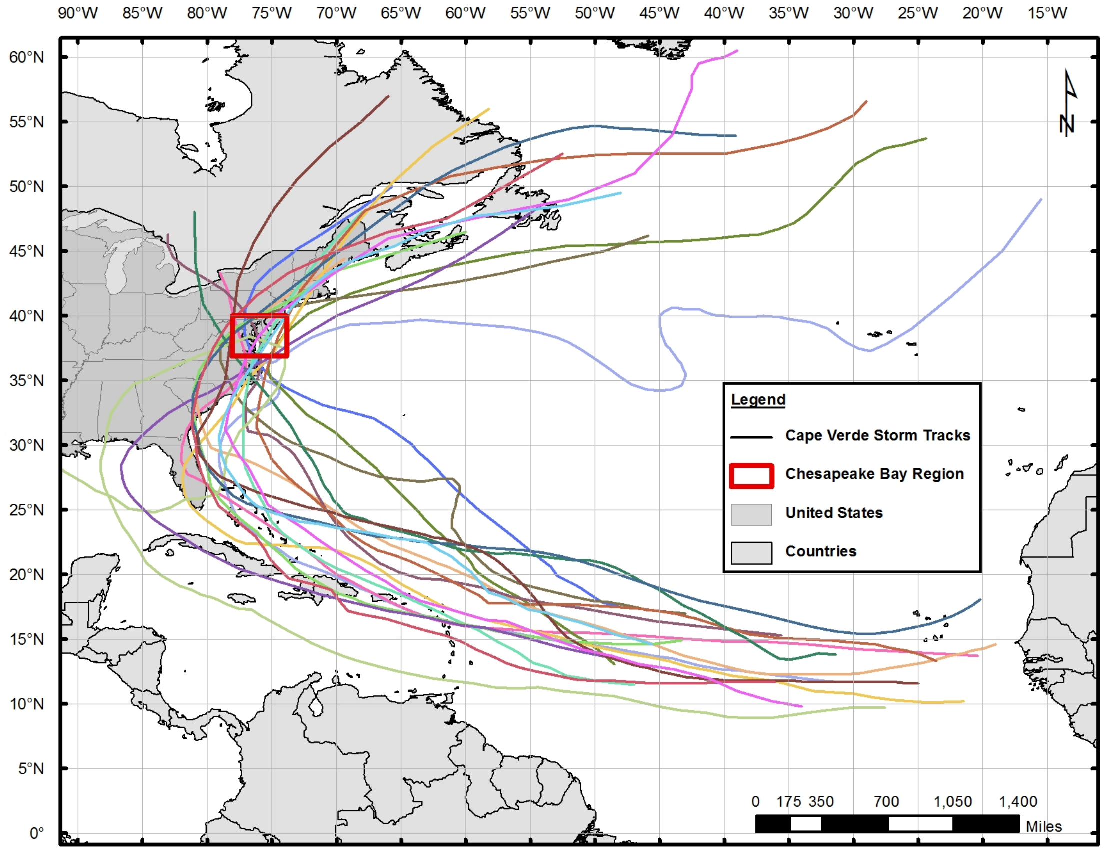


Figure 4.2: Cape Verde Originating TCSs.

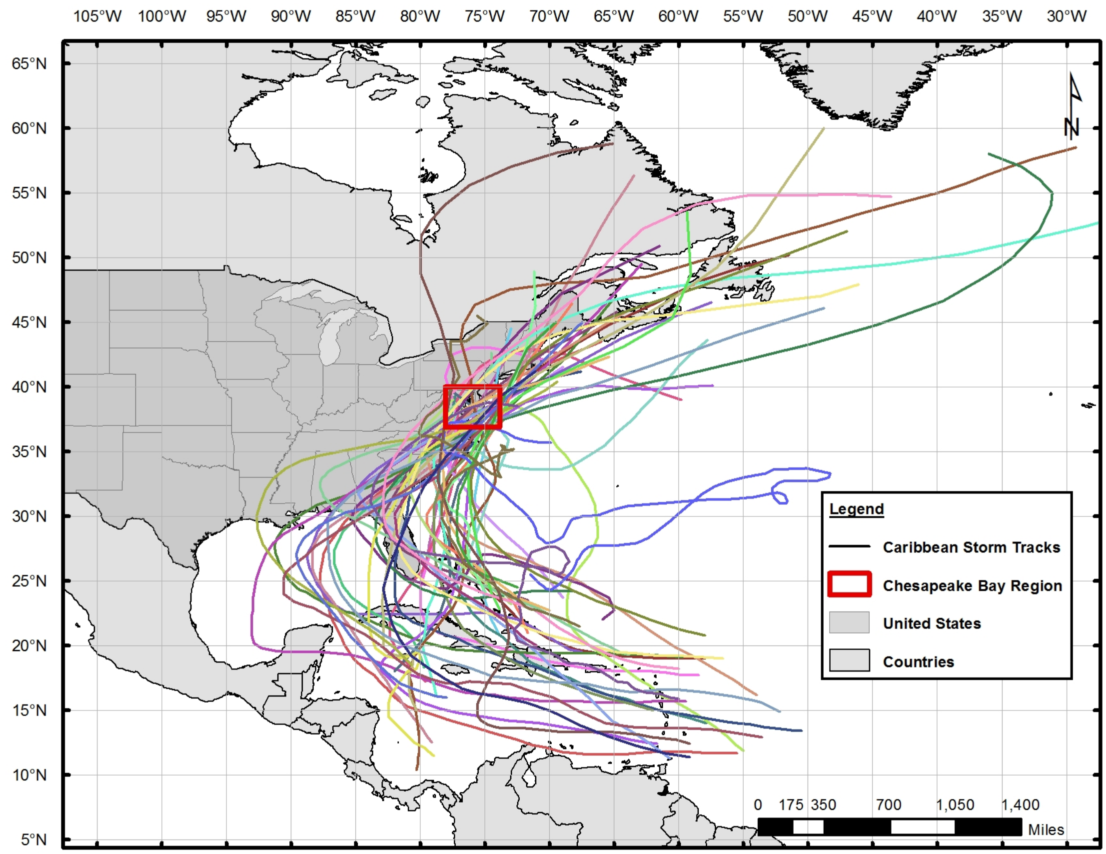


Figure 4.3: Caribbean Originating TCSs.

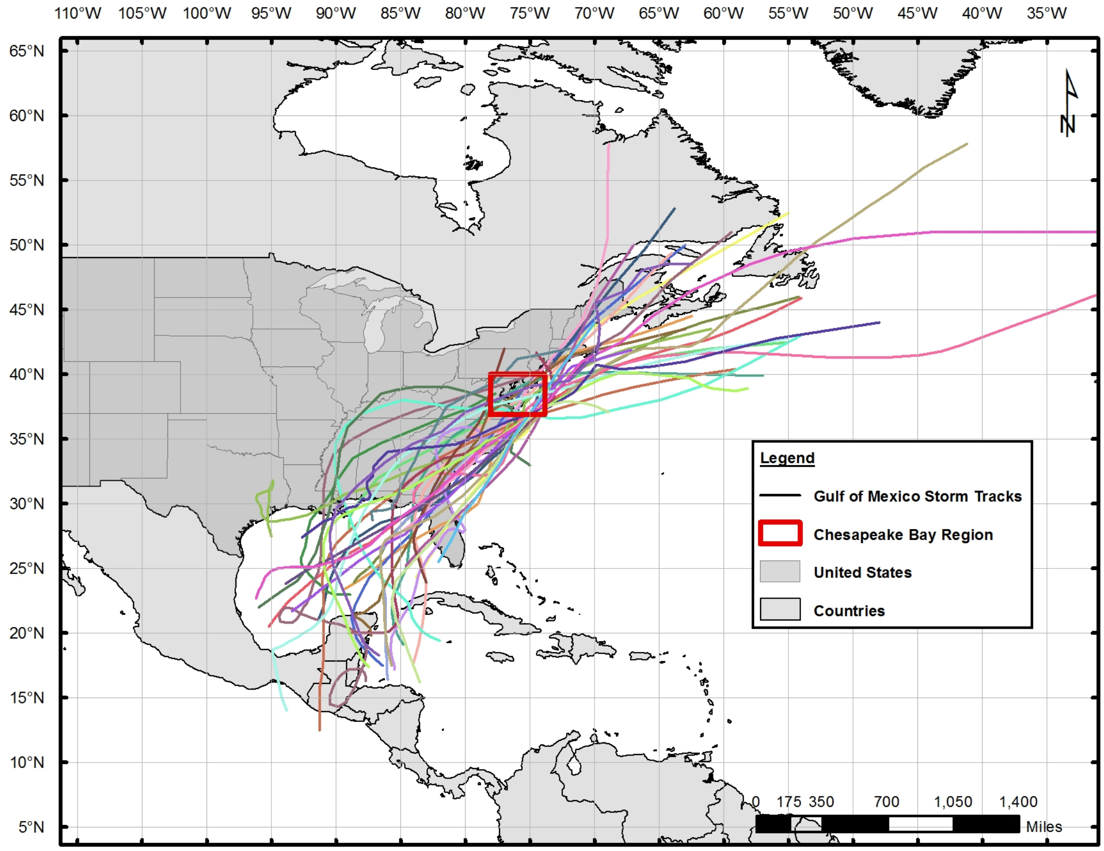


Figure 4.4: Gulf Originating TCSs.

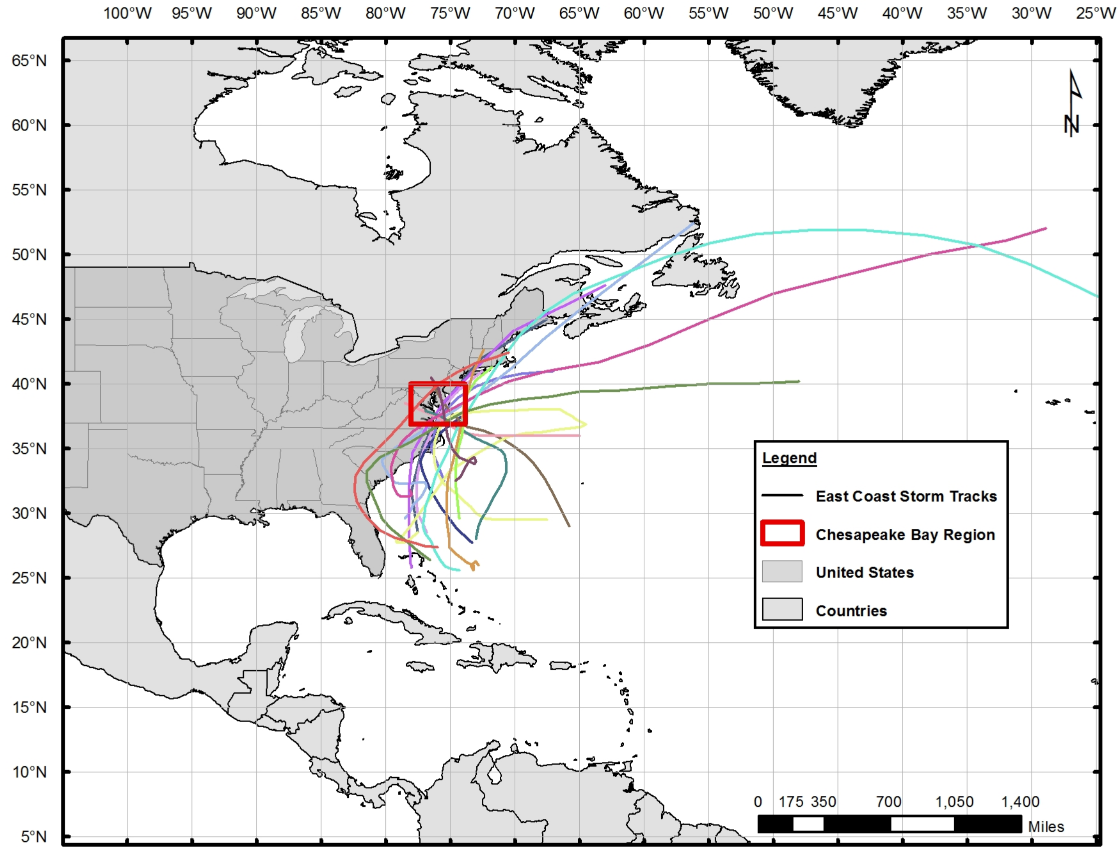


Figure 4.5: East Coast Originating TCSs.

4.2 Path

The second parameter examined is the path that each tropical circulation system took through the region. The path parameter takes into account the point and angle at which the TCS entered the region, direction of travel and length of time that the system spends in the region. Neither one of these variables are more significant than the other (i.e., the point of impact is not necessarily more significant than the angle of impact); they all affect the outcome of the TCS differently with each event. The three variables work together and in general terms, the longer period of time that a tropical circulation system spends over land before entering the CBR, the lower the impact/intensity will be to the CBR. Conversely, a TCS hitting the region directly, with little previous time over land, will have a relatively greater impact on the CBR. The speed of circulation in tropical systems is greatly affected by the system's direction of travel. One side of the system's winds are moving in favor with the direction of travel and are consequently stronger, whereas, the winds on the opposite side are moving against the direction of travel making them weaker. The CBR is unique in that it has a large body of water, the Chesapeake Bay, running in a north-south orientation through the center of the region. This geographic feature has a great affect on the impact experienced depending on how the massive body of water reacts to the introduction of a TCS.

Using the Chesapeake Bay as the focal point of the study, there are seven (7) generalized paths that TCS take through the region. These paths are (along with their respective abbreviations used in the database): (1) land (LAND), (2) coast-crossing (COASTX), (3) land-crossing (LANDX), (4) Eastern Shore (ES), (5) bay (BAY), (6) Atlantic (ATL), and (7) landfalling (LF) (see Figure 4.7).

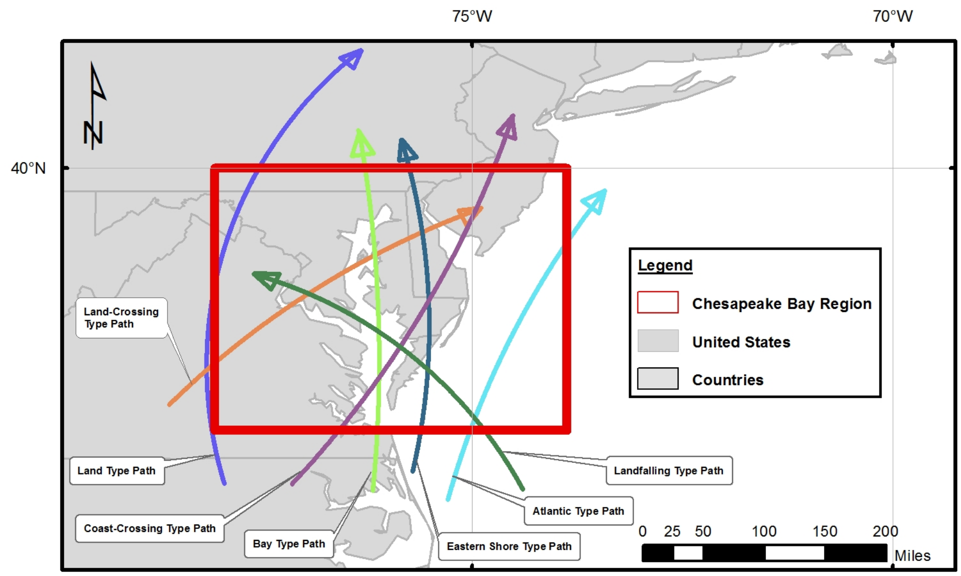


Figure 4.7: General Paths Through the CBR.

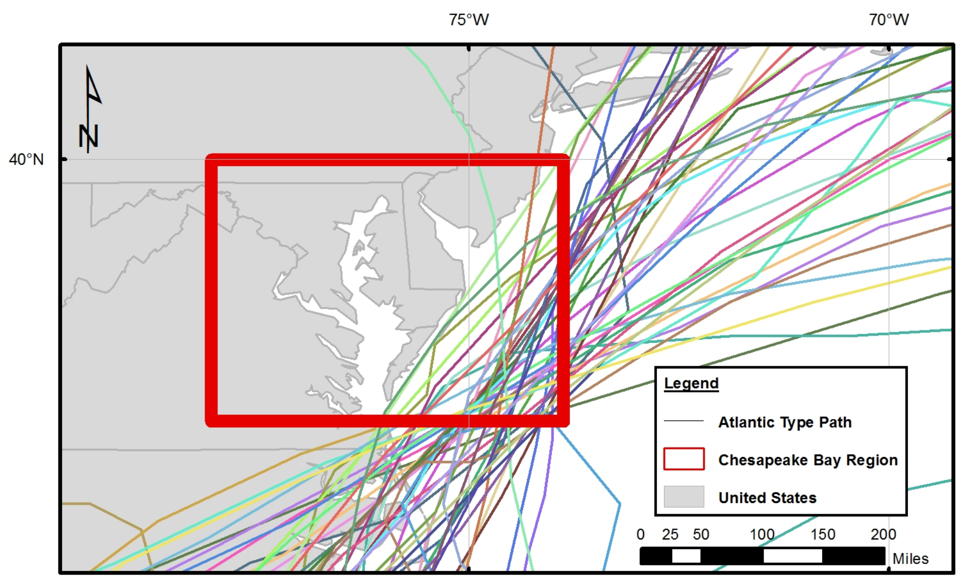
In defining the path types note the north-south orientation of the Bay. The paths are described in terms of their angle of incidence to this orientation. First, land type paths include the storms that passed through the region without crossing the Bay; they pass completely to the West interior of the Bay. Second, coast-crossing type paths move north along the East coast of the US and cross the Bay. Third, land-crossing type paths spend most of their time progressing north well to the interior of the region, but take an easterly turn and cross the bay west to east. Fourth, Eastern Shore type paths include storms that make landfall on the Eastern Shore (Delmarva peninsula) and travel north parallel to the Bay without crossing. Fifth, bay type paths include storms entering the region at the mouth of the Bay and travel north closely along the body of the Chesapeake. Sixth, Atlantic type storms never make landfall in the region, but stay within the set boundaries of the CBR over the Atlantic Ocean.

Finally, seventh, landfalling type paths include storms that make direct landfall in the CBR, mostly to the south of the region, and cross east to west. (See Figures 4.8 – 4.14 for maps of the CBR path types).

In terms of analyzing the various path types, it is not surprising that a majority (21) of the TCS show an Atlantic type path. This is due to the shear size of the CBR leading to the inclusion of the numerous TCSs that tend to stay where the environmental attributes are generally favorable for maintaining the lifespan of a TCS, warm buoyant air over warm water. The other path types are less frequent in comparison to the Atlantic type storms. The frequency counts of the remaining storms are: land type (13), land-crossing type (6), coast-crossing type (6), landfalling (2), Eastern Shore (1), and bay (1) (see Table 4.2 and Figures 4.8 – 4.14). It is interesting to note that the region rarely experiences storms that make landfall or spend a great amount of time over the Delmarva Peninsula and the Bay itself. Also, by the time many TCSs reach the higher latitudes of the Chesapeake Bay Region, they have lost much of their intensity.

Table 4.2: Path of TCSs Through the CBR 1950-2006.

PATH	COUNT
ATLANTIC (ATL)	21
CHESAPEAKE BAY (BAY)	1
COAST-CROSSING (COASTX)	6
EASTERN SHORE (ES)	1
LAND (LAND)	13
LANDFALLING (LF)	2
LAND CROSSING (LANDX)	6
TOTAL	50



4.8: Atlantic Type Paths.

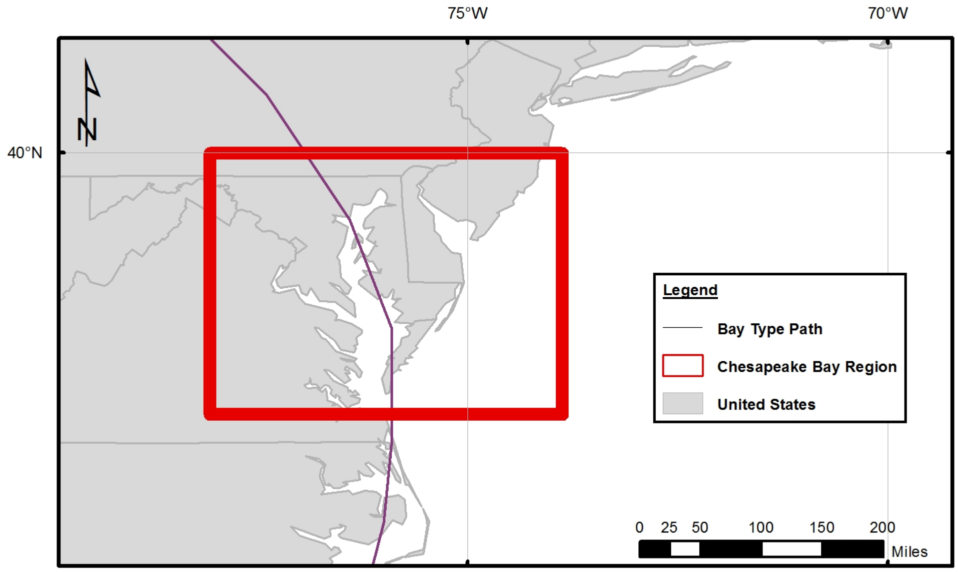


Figure 4.9: Bay Type Paths.

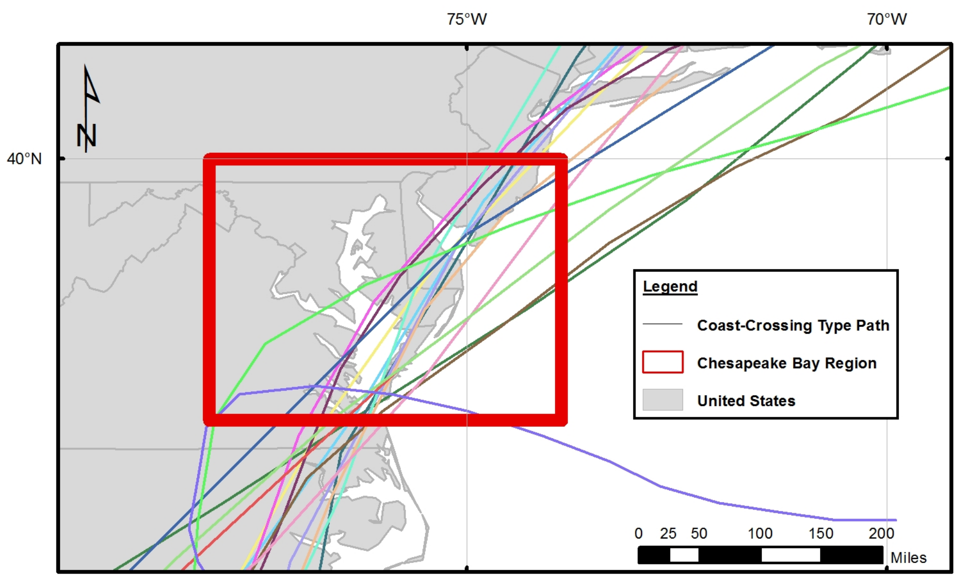


Figure 4.10: Coast-Crossing Type Paths.

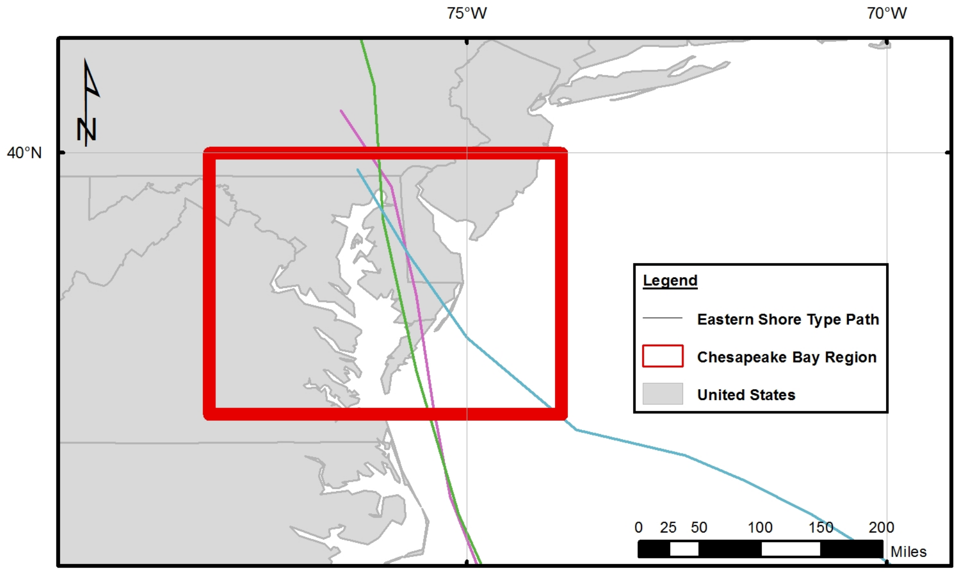


Figure 4.11: Eastern Shore Type Paths.

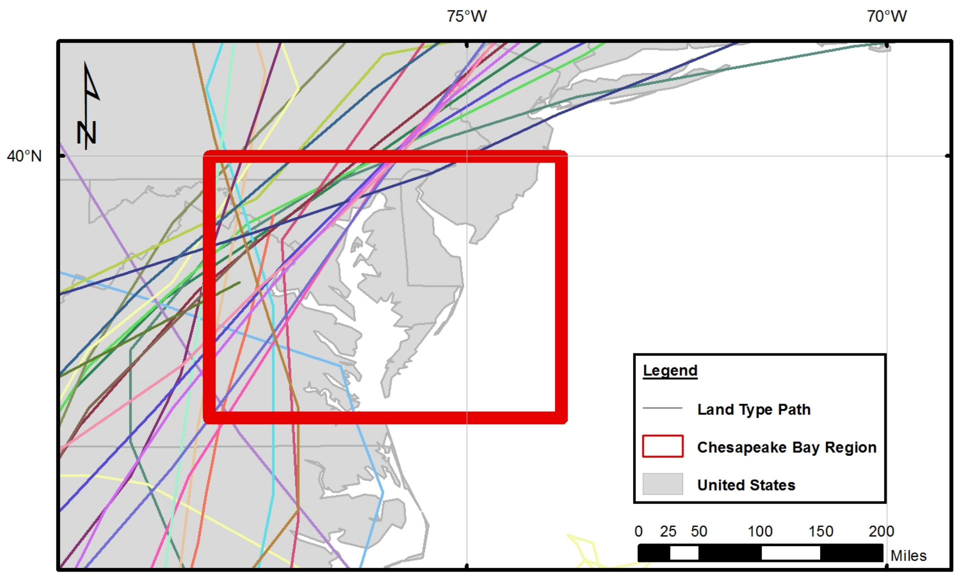


Figure 4.12: Land Type Paths.

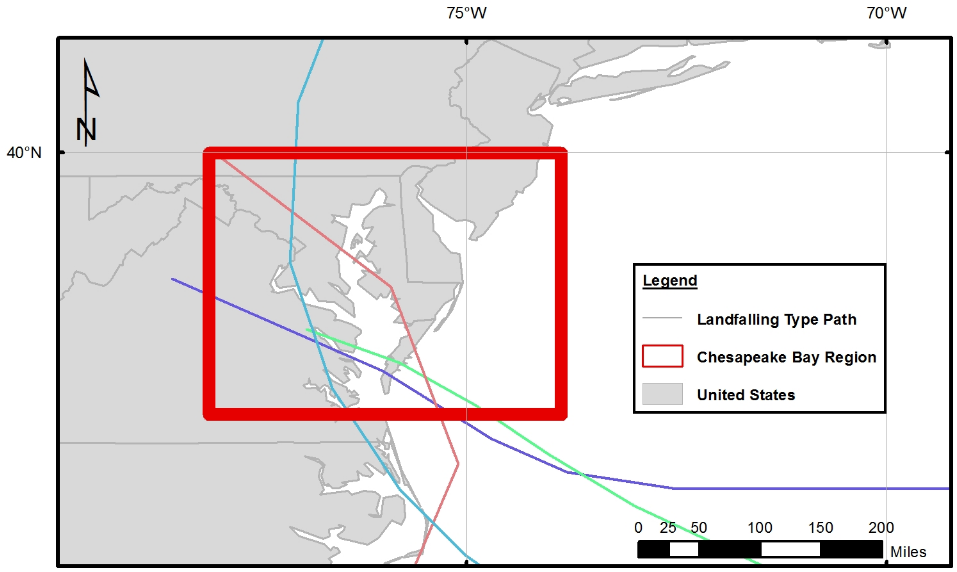


Figure 4.13: Landfall Type Paths.

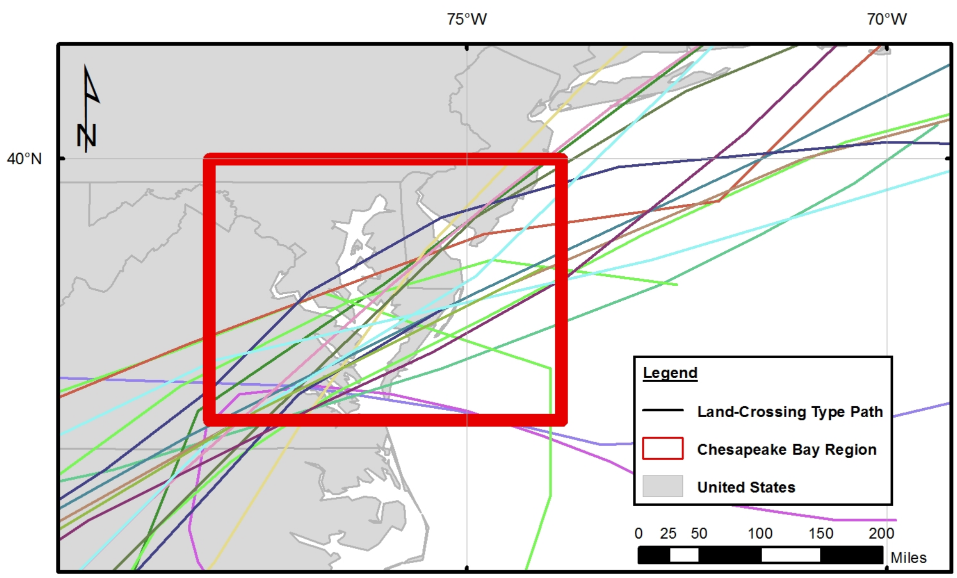


Figure 4.14: Land-Crossing Type Paths.

4.2.1 Path as a Function of Origin

The TCS path can be analyzed as a function of the storm's origin location (see Table 4.3). Cave Verde originating storms mainly take land type paths, with Atlantic type paths the second most numerous. It appears that the Cape Verde type storms make landfall south of the CBR, usually in the Carolinas. The storms would then track northward, staying inland. Storms with Caribbean type origins have mainly Atlantic type and land type paths. There is only one other Caribbean type storm with a land-crossing type path. In the case of these storms, they follow the Gulf Stream past the CBR, or make landfall in the Carolinas and stay completely inland, there is no middle ground. Gulf of Mexico type origin storms mainly have Atlantic type paths. This makes sense as the storms are generated in the warm waters of the Gulf of Mexico and then follow the Gulf Stream northward, rarely veering from the flow of warm water. The same goes for the East coast type originating storms. Again, they are formed in the Gulf Stream, and seldom abandon the course of the warm flow of water.

While it is interesting to find associations between the TCS's origin and the path it takes through the region, more research and analysis is needed to confirm significant relationships. The atmosphere is dynamic and the variables affecting the push and pull of a storm, including ENSO and NAO cycles, vary tremendously from season to season and also within a season.

Table 4.3: Path as a Function of Origin.

	ORIGIN			
PATH	CV	CARI	GULF	EAST
ATLANTIC (ATL)	3	6	7	5
CHESAPEAKE BAY (BAY)	1	0	0	0
COAST-CROSSING (COASTX)	2	0	2	2
EASTERN SHORE (ES)	0	0	0	1
LAND (LAND)	6	5	2	0
LANDFALLING (LF)	0	0	0	2
LAND-CROSSING (LANDX)	1	1	3	1

4.3 Storm Intensity

The storm intensity recorded in the CBR-SDD uses the Saffir-Simpson Scale (SS-scale) ratings as defined by the National Weather Service: National Hurricane Center (NWS-NHC) (Ahrens 2012). The SS-Scale is based on the wind speeds of each system. The categories range from category 1 to category 5, with category 5 possessing the highest wind speeds. The lesser categories in the CBR-SDD include TCSs that have gained extratropical storm (ES) status, tropical depressions (TD) and tropical storms (TS). The extratropical storm category includes storms that have become cold-core systems resembling a more typical mid-latitude cyclone. These storms began as a TCS so they are retained in the database. Tropical depressions have wind speeds between 20 and 34 knots (23 to 39 mph) and have a distinct center of low pressure. Tropical storms with wind speeds of 35 to 64 knots (40 to 74 mph) (Ahrens 2012) are the next strongest TCS. Storms with wind speeds over 64 knots (74 mph) become hurricanes and are categorized according to the SS-Scale categories.

As the storm propagates along its stormtrack, the intensity can and does change depending on factors such as water temperature, humidity, latitudinal location, position in respect to a land mass, etc. The intensity listed in the CBR-SDD is the intensity of the TCS upon entrance in the CBR boundaries. Due to the latitudinal location of the CBR, the majority of the TCSs that reach the CBR have lost much of their strength and have been downgraded to tropical storm status. Even though TCSs have lost strength, they still cause tremendous amounts of damage as they pass through the CBR.

The most frequent category of TCSs experienced in the CBR are storms below hurricane status, with tropical storm and extratropical storm intensity. Even though the TCSs are downgraded to TS or ES does not mean that they lose their ability to cause damage. These systems still have respectable wind speeds and also produce large amounts of rain. This becomes very apparent in the damage analysis. The least frequent category of TCS is category 3 hurricanes. Looking at the overall record since 1851, only three category 3 hurricanes have passed through the region, with one of them occurring within the past fifty years (Bob in 1979). It is noteworthy to mention that out of all the years in the CBR-SDD, two decades stand out with having a greater than average number of tropical storms in this region, coincidentally, they are contiguous decades of 1880 and 1890.

Table 4.4: Category of TCSs in CBR 1950-2006.

CATEGORY	COUNT
EXTRATROPICAL (ES)	11
TROPICAL DEPRESSION (TD)	9
TROPICAL STORM (TS)	20
CATEGORY 1 (CAT 1)	5
CATEGORY 2 (CAT 2)	4
CATEGORY 3 (CAT 3)	1
TOTAL	50

4.3.1 Category as a Function of Origin

The relationship between the category of a TCS and where it originated was analyzed (see Table 4.5). The long tracks of the Cape Verde type TCSs seem to aid in the development of the storm and allow it to maintain strength as it reaches the CBR. Upon entering the CBR, six of the Cape Verde type storms arrive as tropical storms, and five as hurricane strength storms. None of the other origins have resulted in as many hurricane strength TCSs. Caribbean type origin storms reach the CBR mainly as extratropical storms (6), however Caribbean originating storms did result in two TCSs of hurricane strength. Gulf of Mexico type origin storms also tend to be weaker with five extratropical storms, and one occurrence of a hurricane strength storm. These storms (Caribbean and Gulf of Mexico types), on average spend some amount of time over land as they move toward the CBR. By the time they reach the CBR, they have been significantly weakened. Finally, East coast type originating storms typically reach the CBR as tropical storms (9), with one occurrence of a category 2 storm. This is also the origin that generated the only category 3 storm in the study. These storms with the exception of a few stay in close contact with the warm waters of the Gulf Stream so they do not lose intensity as they move northward. They are able to arrive at the CBR as tropical storms and sometimes as hurricanes.

Table 4.5: Category as a Function of Origin.

	ORIGIN			
CATEGORY	CV	CARI	GULF	EAST
EXTRATROPICAL (ES)	0	6	5	0
TROPICAL DEPRESSION (TD)	2	3	4	0
TROPICAL STORM (TS)	6	1	4	9
CATEGORY 1 (CAT 1)	3	1	1	0
CATEGORY 2 (CAT 2)	2	1	0	1
CATEGORY 3 (CAT 3)	0	0	0	1

4.4 Seasonality

The long-term frequency of TCSs in the CBR can be analyzed by looking at the decadal cycles of activity (see Figure 4.15). The most active decade in the 1950-2006 time period is the most recent decade, 2000-2006. Note that this study considered data only through 2006 of the final decade. There are no decades in this time period that did not experience a TCS of some type. In an average decade, the CBR experiences between 8 and 9 TCSs with tropical storms as the most frequent type to impact the region. The CBR has experienced 10 storms of hurricane strength since 1950 with at least one hurricane during each decade.

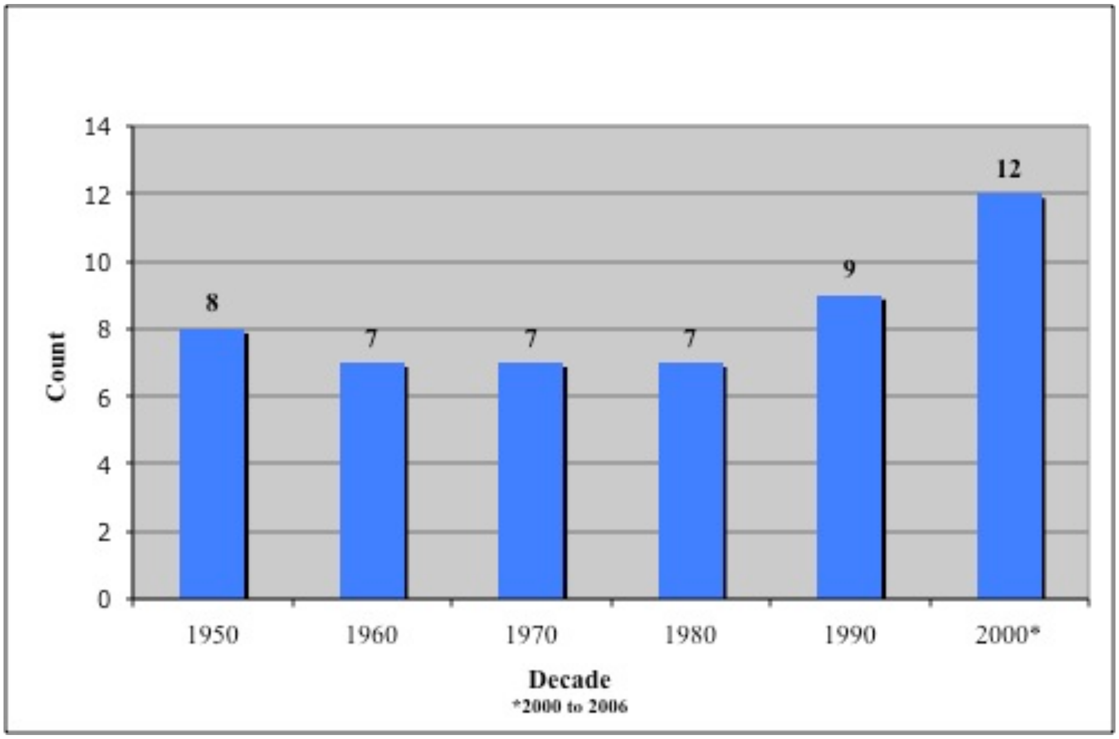


Figure 4.15: Frequency of TCSs by Decade 1950-2006.

The driving forces behind the frequency of TCS activity at this latitude depends on the cycles of ENSO which affects the overall frequency of storms, and the NAO which affects the direction of the storm track (Elsner, et al. 2000). ENSO determines whether the season will be active or not in terms of TCSs. There are two parts or extremes to the ENSO cycle, El Nino and La Nina. During El Nino years, there are fewer TCS occurrences due to more upper-level shearing winds that discourage their evolution. La Nina years typically have more TCSs due to the lack of upper-level shear. An NAO with an excited or recurving pattern (positive phase) directs TCSs to higher latitudes and would result in more direct CBR strikes. An

NAO with a relaxed or non-recurving pattern (negative phase) would direct TCSs to lower latitudes with storms nearing land near Florida or the Gulf of Mexico.

The overall seasonality of TCS activity in the CBR resembles the seasonality of the greater Atlantic Basin (see Figure 4.16). The season extends from June to November; the peak of the TSC season is in September (see Figures 4.17A – 4.17F). The earliest storm entered the CBR at the end of May, Alma an extratropical storm in 1970.

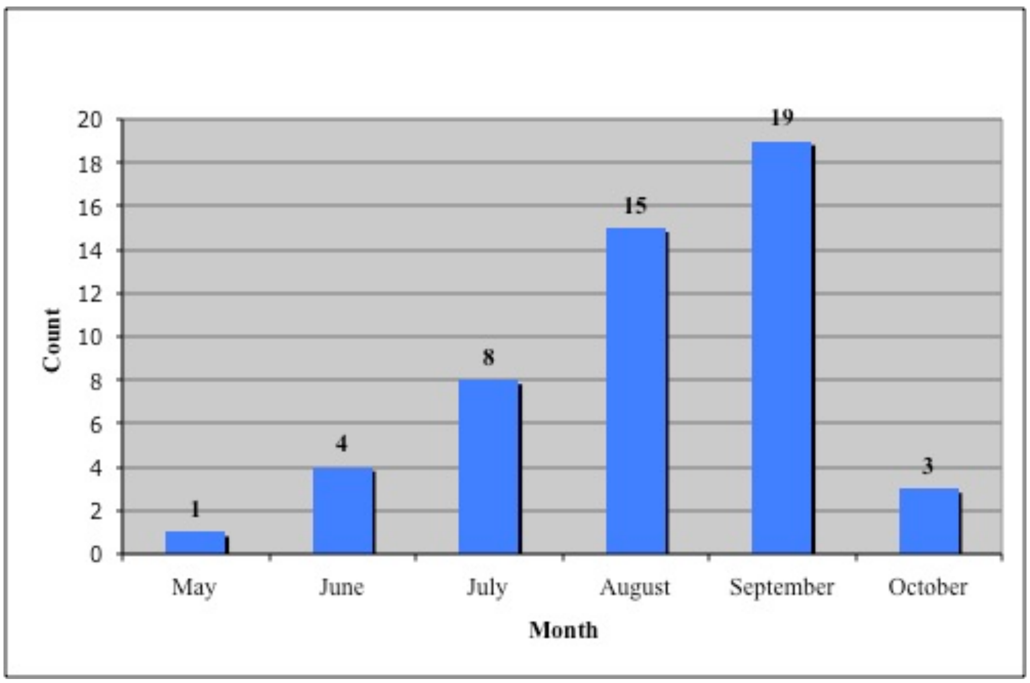


Figure 4.16: Seasonality of TCSs in CBR 1950-2006.

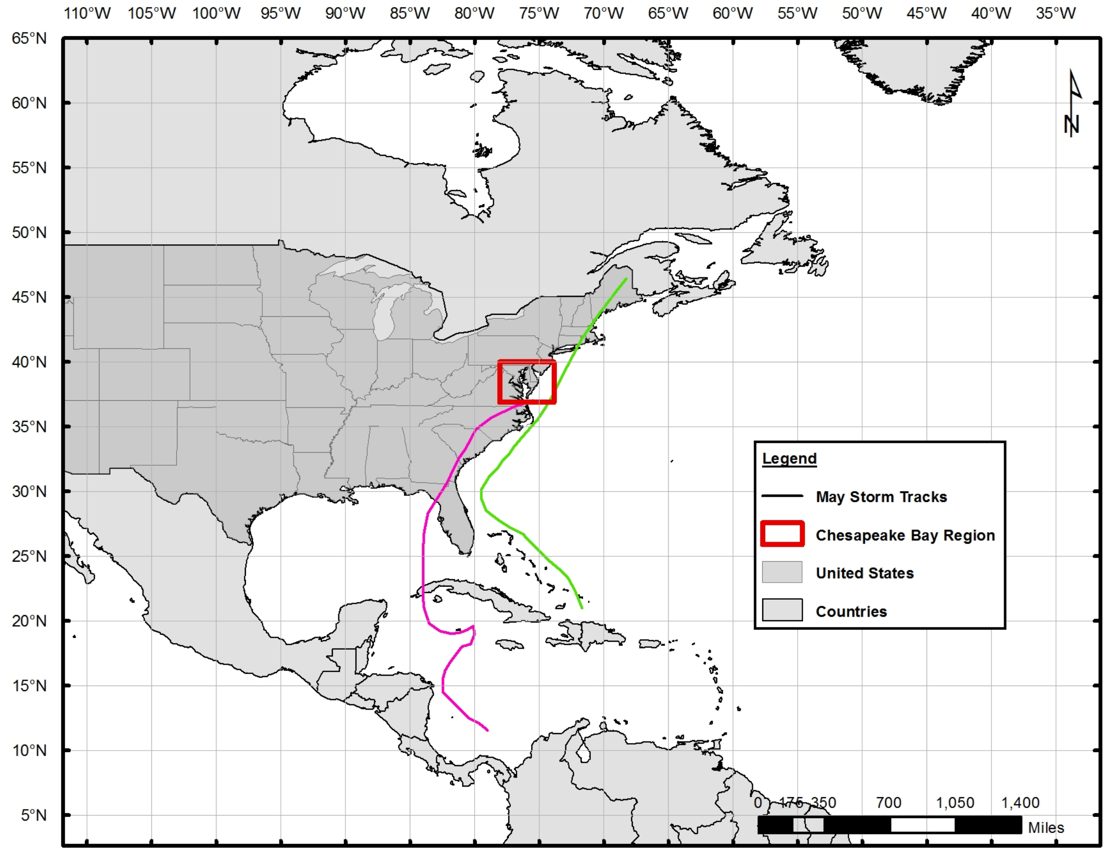


Figure 4.17A: May TCSs.

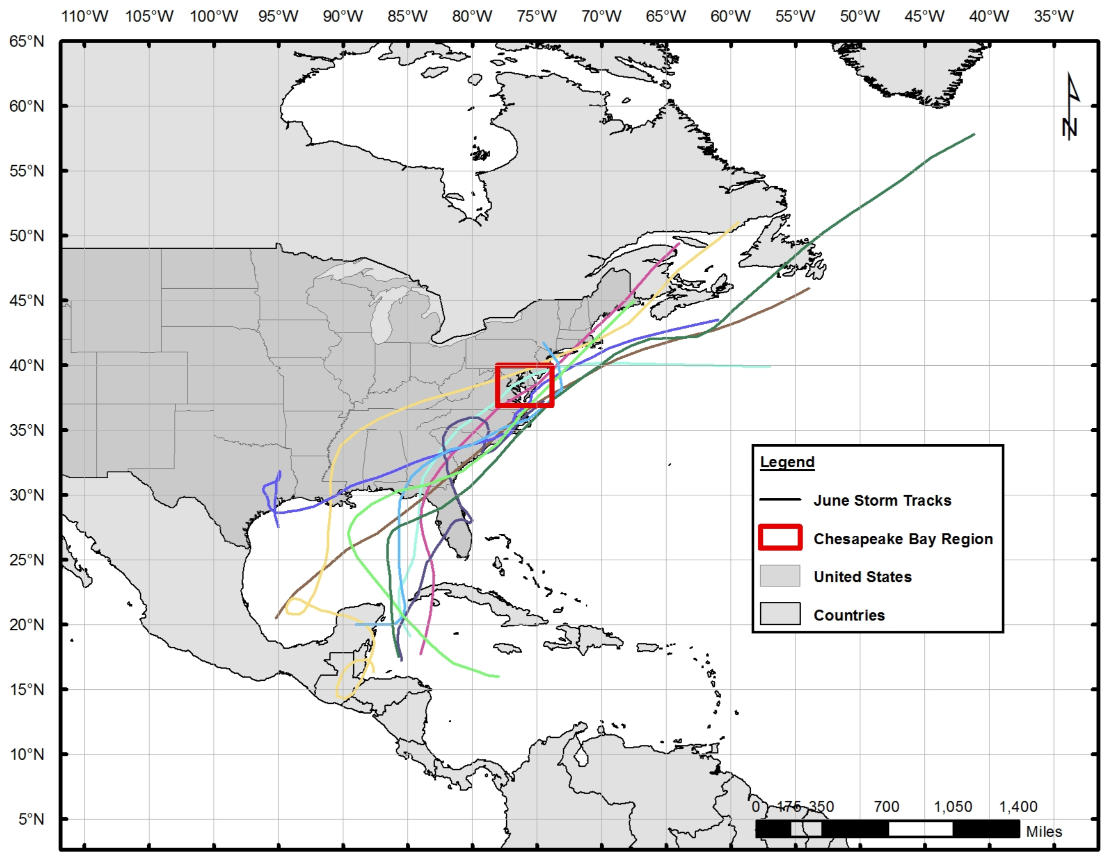


Figure 4.17B: June TCSs.

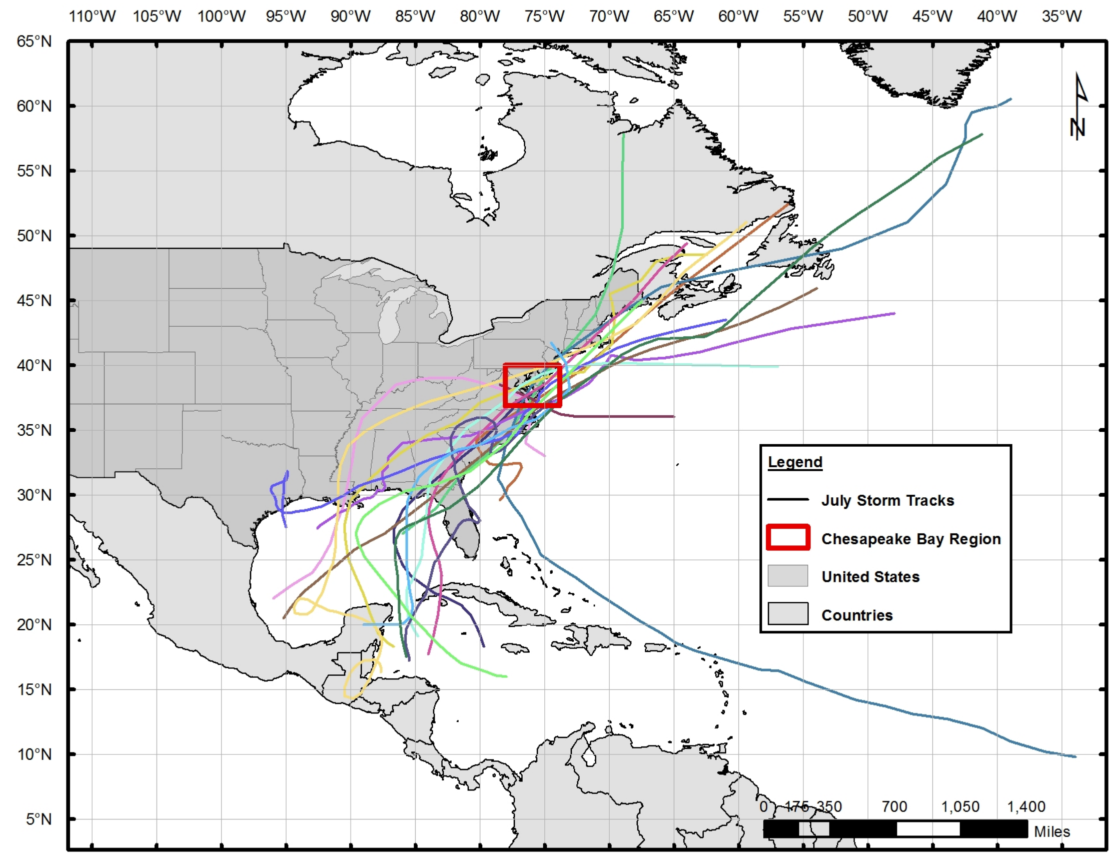


Figure 4.17C: July TCSs.

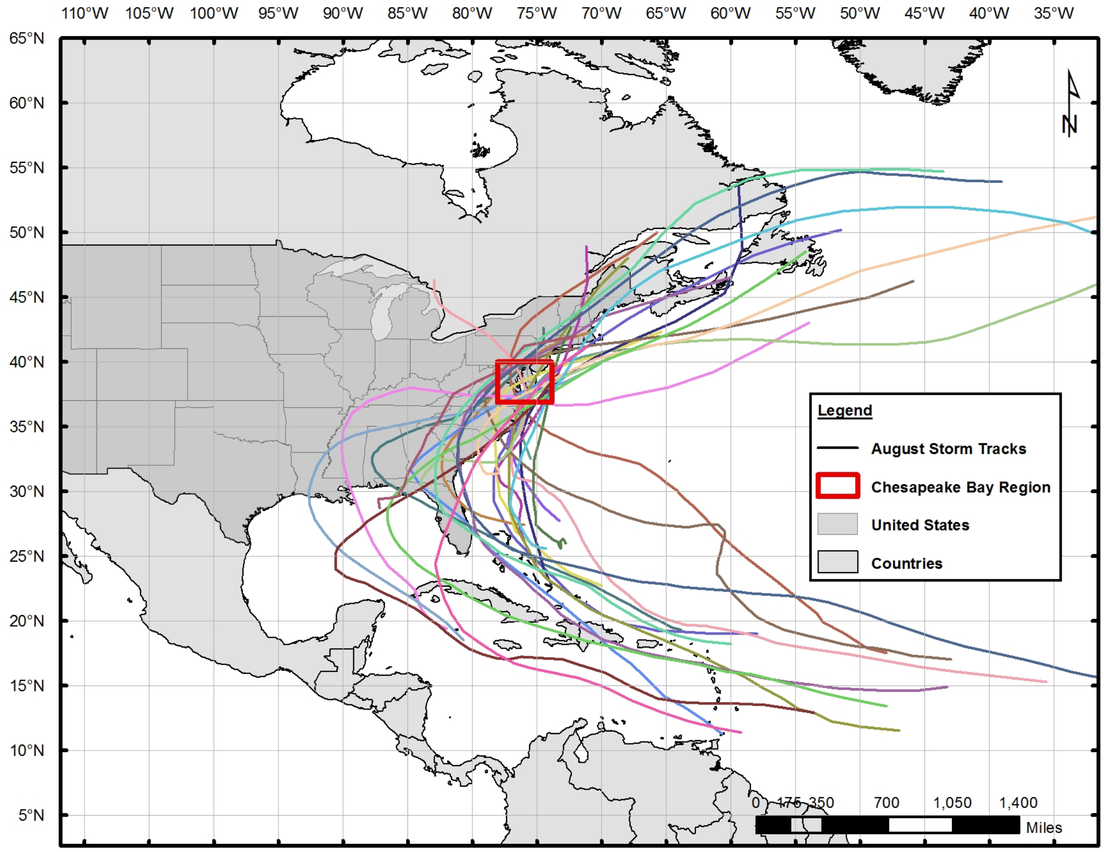


Figure 4.17D: August TCSs.

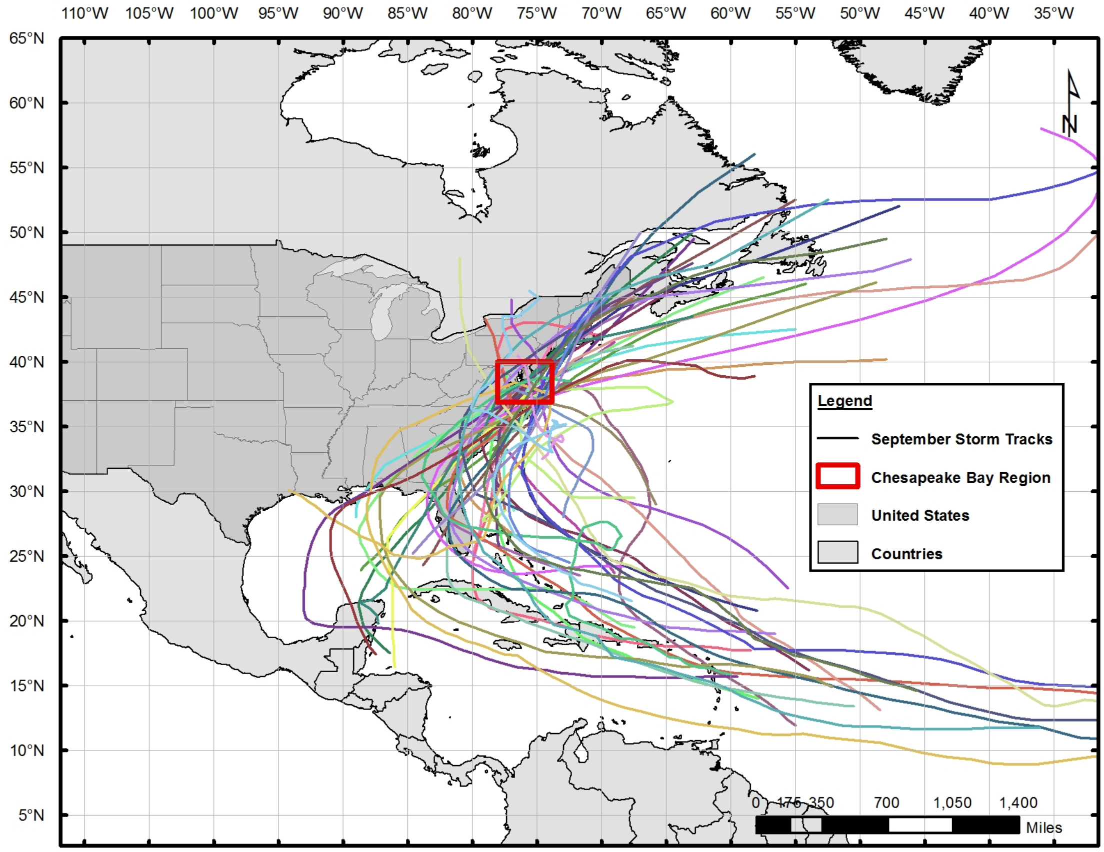


Figure 4.17E: September TCSs.

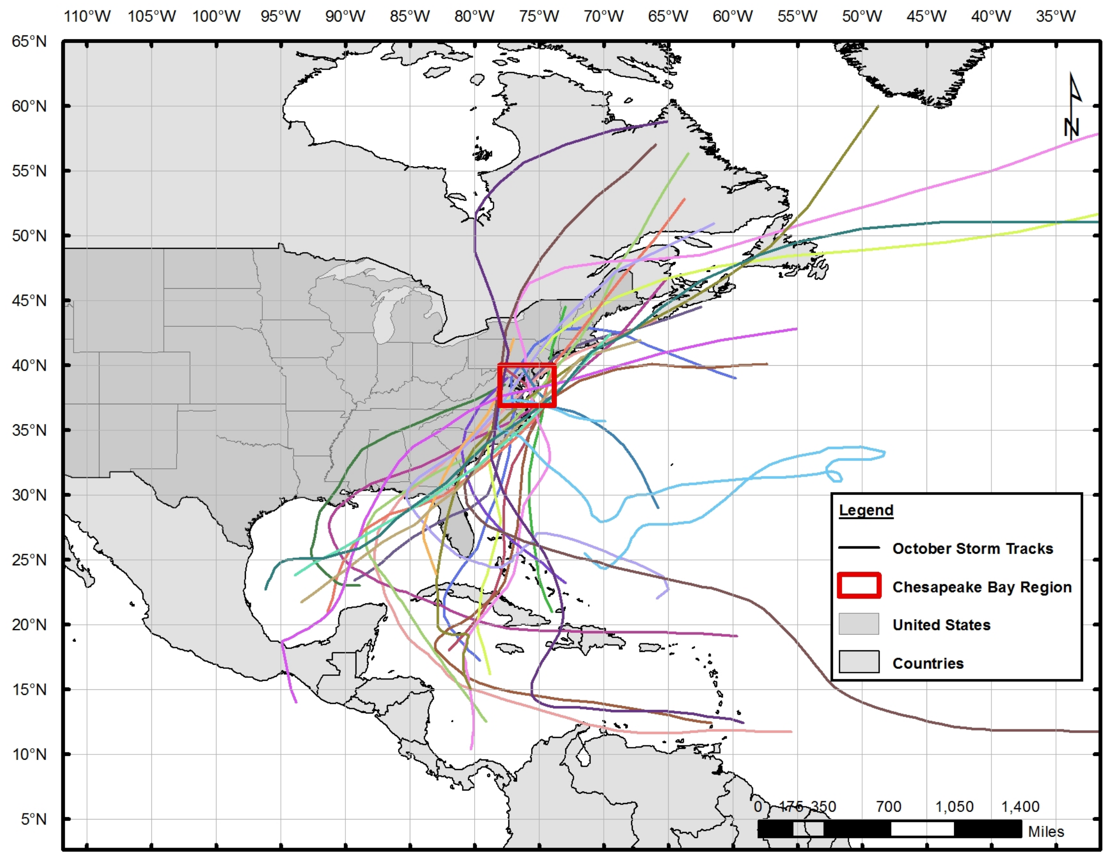


Figure 4.17F: October TCSs.

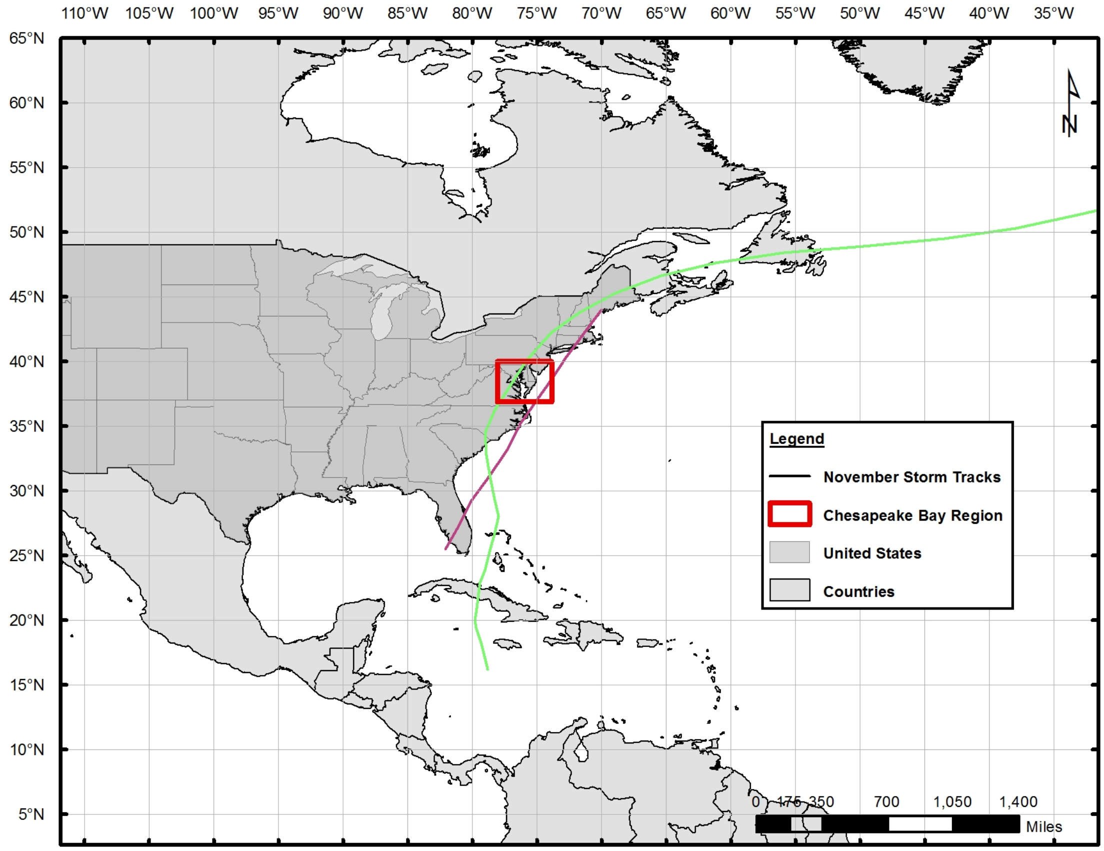


Figure 4.17G: November TCSs

(Note: Map provided for informational purposes only. There are no November TCSs in the 1950-2006 time period.)

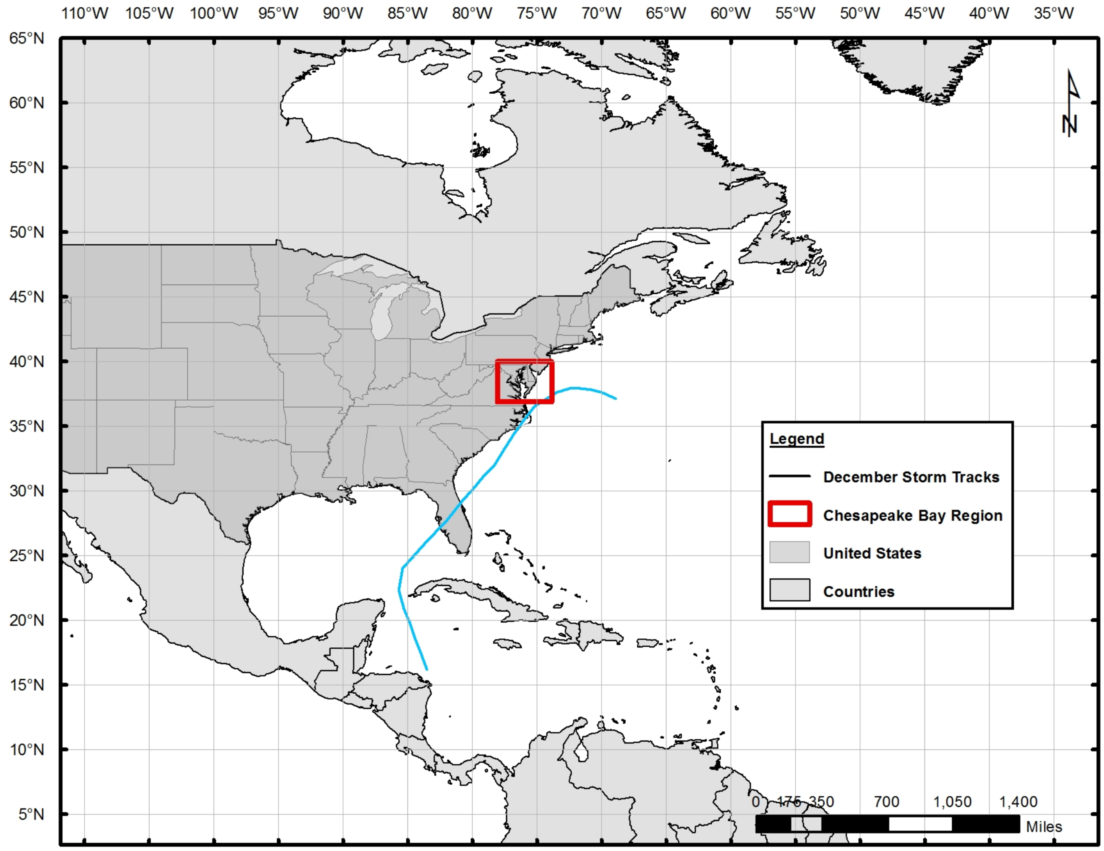


Figure 4.17H: December TCSs

(Note: Map provided for informational purposes only. There are no December TCSs in the 1950-2006 time period.)

Chapter 5

DAMAGES

Over the course of the CBR-SDD time period from 1950 to 2006, the CBR has an accrued damage total of $4,158,431,635 ($14,642,055,086 in 2011 USD) from TCSs. The most costly storm to date is Agnes in 1972 known as the "Billion Dollar Storm", a tropical storm causing $2,400,000,000 ($12,915,158,400 in 2011 USD) in damages mainly due to flooding in Chesapeake Bay watersheds. In addition to the climatological factors discussed in Chapter 4, throughout all the TCS reports, four main causes of damage are described: storm surge, stream flooding, high wind, and 'other'. The first three types are self explanatory, whereas, the damage category of 'other' includes any complicating factors causing damage to property or infrastructure, injury, or death. Some examples are TCS induced tornadoes, and car accidents that occur during a TCS event. Damage cost estimates are first compiled by climatological factors, and then for specific damage types.

5.1 Damage Cost by Climatological Factors: Origin, Path, and Category

5.1.1 Damage Cost by Origin

In terms of TCS origin, the highest amount of damage is the result of TCSs that are generated in the Gulf of Mexico. It is worthy to note that the overall damage cost as well as the cost per Gulf of Mexico originating storm are both the highest in this category (see Table 5.1). This may be attributed to the fact that most of the Gulf of Mexico type TCSs have an Atlantic type path. (The cost of damage by path is discussed in section 5.2. Note that Atlantic type paths accrue the highest cost of damage.) The second highest damage cost comes from Cape Verde originating storms. Most Cape Verde type storms have land type paths, the second highest damage causing path type. The third and fourth highest damage costs by origin are by Caribbean and East Coast originating storms, respectively. These storms do not have the same lifespan in warm waters as the higher damage causing origin types, and thus arrive in the CBR with weaker intensity.

Table 5.1: Cost of Damages by Origin.

COST OF DAMAGES BY ORIGIN	COST USD	PER STORM
CV (13)	$1,364,640,000	$104,972,308
CARI (12)	$229,989,000	$19,165,750
GULF (14)	$2,563,680,175	$183,120,013
EAST (11)	$122,460	$11,133

5.1.2 Damage Cost by Path

TCSs with Atlantic type paths accrue the most cost overall and per storm (see Table 5.2). This may be due to the fact that there is little to no landfall to weaken the system, so it retains its strength as it passes through the area. The sensitive coastal areas in the CBR (VA, MD, DE, NJ) may experience significant damage as storms move along the coast just offshore. In addition, coastal development is relatively high in the CBR and vulnerable to coastal flooding in particular. Beach, infrastructure, and sensitive area mitigation (and replenishment efforts in the wake of a storm) can be very expensive. The second most expensive damage costs come from TCSs with land type paths. Although a different type of geographic region is encountered, land type paths typically encounter more of the built environment; more property can be destroyed as the storm spends most of its time in the CBR on land. The same goes for land-crossing type paths, the third highest damage cost. The lowest damage costs (total and per storm averages) come from the bay type, coast-crossing type, Eastern Shore type, and landfalling type paths.

Table 5.2: Cost of Damages by Path.

COST OF DAMAGES BY PATH	COST USD	PER STORM
ATLANTIC (21)	$2,722,807,650	$129,657,507
BAY (1)	$5,000,000	$5,000,000
COAST-CROSSING (6)	$1,495,000	$249,167
EASTERN SHORE (1)	$55,000	$55,000
LAND (13)	$1,183,111,675	$91,008,590
LANDFALLING (2)	$4,810	$2,405
LAND-CROSSING (6)	$245,957,500	$40,992,917

5.1.3 Damage Cost by Storm Intensity

The cost of damage by storm intensity seems to go against what is expected when the TCSs of hurricane strength are considered. The cost per storm does follow the expected trend in cost until it reaches category 2 storms where the trend breaks down. Based on the ranking system, the category 3 storm should have had the highest cost per storm, but the highest is in fact category 1. This may be credited to the fact that the overall sample size of category 1 and above storms is too limited to provide better result for TCSs of greater strength. Another reason may be that the TCSs of higher categories missed the areas with higher populations and built environments. These storms may be stronger, but since there are few occurrences, they may have affected areas with less property to damage. It is interesting to note that the category 3 storm has a $0 damage cost. Consequently, there was no available damage report for this storm; the event has no associated cost.

The highest overall cost comes from tropical storms simply because most of the storms in the region are tropical storms. However, the highest cost per storm is caused by category 1 hurricanes (see Table 5.3).

Table 5.3: Cost of Damages by Storm Intensity.

COST OF DAMAGES BY INTENSITY	COST USD	PER STORM
EXTRATROPICAL (11)	$180,895,000	$16,445,000
TROPICAL DEPRESSION (9)	$340,094,175	$37,788,242
TROPICAL STORM (20)	$2,565,954,210	$128,297,711
CATEGORY 1 (5)	$1,013,155,500	$202,631,100
CATEGORY 2 (4)	$58,332,750	$14,583,188
CATEGORY 3 (1)	$0	$0

5.2 Damage Cost by Type

In the case of the CBR, the most costly cause of damage is flooding, causing an estimated $2,899,944,884 in damages (or 69.5% of the total damage amount) during the 1950 to 2006 time period. The second most costly cause of damage is storm surge, resulting in $673,363,883 in damages (or 16.2% of the total damage amount). High wind speed result in $370,804,544 (or 8.9% of the total) of damage cause. Finally, the damage category of 'other' was responsible for $224,318,325 in damage (or 5.4% of the total damage amount). These damage costs are according to the dollar amount that was recorded at the time of the event. When the costs are calculated in terms of 2011 US dollars using inflation rates, the costs increase dramatically, more than three and a half times the actual recorded amount. It is important to notice the increase in costs in regard to wind damage from actual costs reports in 2011 dollars. Actual reported costs have wind damage as the third largest damage causing type, whereas, in 2011 dollars, winds are the second. Timing, in terms of decade, matters in this case. There are more wind-type TCSs occurring between 1950 and 1970 compared to storm surge. The inflation rates are much higher in this time span which give wind-type TCSs an advantage in cost. See Table 5.4 for damage amounts by decade, and Table 5.5 for the estimates in 2011 equivalent dollars (Rate Index 2012).

Table 5.4: Cost of Damages By Type.

Cost of Damages (USD)	Storm Surge	Flooding	Wind	Other
1950	$15,169,000	$83,181,750	$57,288,500	$4,473,250
1960	$54,825	$99,039,750	$361,450	$5,201,375
1970	$0	$2,183,154,988	$127,808,063	$165,401,700
1980	$22,342,358	$28,810,722	$29,929,231	$0
1990	$101,539,700	$385,231,675	$26,211,550	$276,750
2000*	$534,258,000	$110,526,000	$129,205,750	$48,965,250
TOTAL	$673,363,883	$2,889,944,884	$370,804,544	$224,318,325
	TOTAL	**DAMAGES**	**$4,158,431,635**	

Table 5.5: Cost of Damages By Type in 2011 USD Equivalent.

Cost of Damages (2011 USD)	Inflation Rate	Storm Surge	Flooding
1950	732.18%	$126,233,809	$692,224,216
1960	602.71%	$385,263	$695,966,981
1970	329.35%	$0	$9,373,480,730
1980	114.96%	$48,028,159	$61,932,852
1990	50.03%	$152,339,301	$577,960,385
2000*	21.22%	$647,601,903	$133,974,312
TOTAL		$974,588,436	$11,535,539,477

(Cont.)

Cost of Damages (2011 USD)	Inflation Rate	Wind	Other
1950	732.18%	$476,745,043	$37,225,617
1960	602.71%	$2,539,963	$36,550,832
1970	329.35%	$548,750,051	$710,160,138
1980	114.96%	$64,337,252	$0
1990	50.03%	$39,278,871	$369,072
2000*	21.22%	$156,617,008	$59,353,326
TOTAL		$1,288,268,188	$843,658,985

TOTAL (2011 USD)	**$14,642,055,086**

The cost of damages in the CBR is influenced by several factors including the prevailing climate cycles, the TCS-specific climatological factors, and types of damage defined in this study. Each storm has a unique combination of these factors that contribute in determining the overall cost of damage caused as the TCS moves through the region, but it is the damage type (storm surge, flooding, wind, and other damage factors) that has the most influence on the overall cost of damage resulting from a TCS event.

Chapter 6

SUMMARY & CONCLUSION

6.1 Summary

A climatology of the TCSs affecting the CBR was built using storm track information collected from NOAA's Historical Hurricane Track Generator. This information was then processed and used to complete a damage assessment for the region. Initial TCS information for the region including all storm intensities, pressure, and wind speed measurements at each time step, along with the spatial representation of the path were collected for the time period beginning in 1851 and ending in 2006. This information was combined with damage data collected from NCDC's Storm Event database (SED) to investigate relationships between the TCSs and damages caused in the CBR for the 1950 to 2006 time period. There were a total of 50 storms affecting the CBR during this later period.

The major climatolological conclusions identified are listed below (1950-2006):

Place of origin (and the associated storm count):

- Gulf of Mexico (14) – most experienced
- Cape Verde (13)
- Caribbean (12)
- East Coast (11)

Path through CBR (and the associated storm count):

- Atlantic (21) – most experienced
- Land (13)
- Coast-Crossing (6)
- Land-Crossing (6)
- Land falling (2)
- Eastern Shore (1)
- Chesapeake Bay (1)

Storm intensity (and the associated storm count):

- Tropical Storm (20) – most experienced
- Extratropical (11)
- Tropical Depression (9)
- Category 1 Hurricane (5)
- Category 2 Hurricane (4)
- Category 3 Hurricane (1)

Seasonality (and the associated storm count):

- May (1)
- June (4)
- July (8)
- August (15)
- September (19) – most experienced

- October (3)

The damage assessment provided the following major results:

- There is no significant trend in damage amounts over time.
- The most costly storm to date was Agnes in 1972 (a tropical storm) costing $2,400,000,000 ($12,915,158,400 in 2011 USD).
- The most costly damage type identified is flooding, causing a total of $2,889,944,884 ($11,535,539,477 in 2011 USD).
- Total of all damages equals $4,158,431,635 USD, however;
- There is a large difference between the cost of damage at the time of the storms and the 2011 USD equivalency of $14,642,055,086 (more than 3.5 times the actual amount!)
- In terms of further investigation, perhaps the utilization of median damage costs, rather than averages, would aid in eliminating any skew introduced by high ranking storms such as Agnes in 1972.

6.2 Conclusion

TCSs are complex systems that operate within a larger dynamic system, the atmosphere. The variables that determine the evolution and fate of a TCS are unique for each storm. A general categorical system is built in order to analyze TCSs and determine damage costs in the Chesapeake Bay Region. Though the categorization used takes into account several variables, it is only a first step in understanding exactly what determines the cost a TCS may accrue in an area.

Though the frequency in storms over the past decades is relatively stable, the trend in damage costs will amplify as property values rise along with the increase of the infrastructure and the built environment. In other words, as a TCS affects a region like the Chesapeake, there is simply more built environment to be damaged. Examples shown in this study reveal that even the less powerful storms can cause tremendous damage. It is important to take all tropical circulation system storm warnings seriously and prepare accordingly whether the system is a hurricane or a storm below hurricane strength.

The damage ranking system used in this thesis is applicable in any region affected by TCSs. It is useful in determining the types of damage that most greatly affect the region, and in mitigating these damage types. Most importantly, and also the motivation behind the study, is that it is extremely useful in describing storm impacts to those inside and outside of the weather and climate field. The means used in this thesis can be used as a first step to inspire a more intense and specific statistical study that should be performed to improve the understanding of how TCSs affect an area.

REFERENCES

Ahrens, C. Donald, 2012. Meteorology Today: An Introduction to Weather, Climate and the Environment. Tenth Edition. Brooks/Cole.

Balling, R., and Cerveny, R., 2006. Analysis of tropical cyclone intensification trends and variability in the North Atlantic Basin over the period 1970-2003. Meteorology and Atmospheric Physics 93: 45-51.

Brady, D., 1976. Are the Chesapeake Bay Waters Warming up? Chesapeake Science 17(3) 225-27.

Chesapeake Bay Program. http://www.chesapeakebay.net, http://www.chesapeakebay.net/about.htm, http://www.chesapeakebay.net/indicators/indicator/chesapeake_bay_watershed_population. (Last accessed February 27, 2012).

Cronin, T., Dwyer, G., Kamiya, T., Schwede, S., and Willard, D., 2003. Medieval Warm Period, Little Ice Age and 20th Century temperature variability from Chesapeake Bay. Global and Planetary Change 36: 17-29.

Cronin, T., Willard, D., Karlsen, A., Ishman, S., Verardo, S., McGeehin, J., Kerhin, R., Holmes, C., Colman, S., and Zimmerman, A., 2000. Climatic variability in the eastern United States over the past millennium from Chesapeake Bay Sediments. Geology 28(1) 3-6.

Crossett, Kristen M., Culliton, Thomas J., Wiley, Peter C., and Goodspeed, Timothy R., 2004. Population trends Along the Coastal United States. NOAA Special Projects: Coastal Trends Report Series.

Downton, M., and Pielke, R., 2005. How Accurate are Disaster Loss Data? The Case of U.S. Flood Damage. Natural Hazards 35: 211-28.

Elsner, J., Liu, K., and Kocher, B., 2000. Spatial Variations I Major U.S. Hurricane Activity: Statistics and a Physical Mechanism. Journal of Climate 13: 2293-2305.

ESRI 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute.

Keim, B., Muller, R., and Stone, G., 2004. Spatial and temporal variability of coastal storms in the North Atlantic Basin. Marine Geology 210: 7-15.

Li, M., Zhong, L., Boicourt, W., Zhang, S., and Zhang, D., 2006. Hurricane-induced storm surges, currents and destratification in a semi-enclosed bay. Geophysical Research Letters 33: 1-4.

Landsea, C., 1993. A Climatology of Intense (or Major) Atlantic Hurricanes. Monthly Weather Review 121:1703-1713.

Ludlum, David, 1963. Early American Hurricanes, 1492-1870. American Meteorological Society.

Microsoft® Excel® 2004 for Mac, 11.6.3 (110113), © 2004 Microsoft Corporation.

Miller, David W., Harding Jr., Lawrence W., Adolf, Jason E., 2006. Hurricane Isabel generated an unusual fall bloom in Chesapeake Bay. Geophysical Research Letters 33: L06612.

NCDC, Storm Events database. http://www.ncdc.noaa.gov/stormevents/. (Last accessed November 19, 2012).

NOAA. Historical Hurricane Tracks. http://www.csc.noaa.gov/hurricanes/#. (Last accessed February 27, 2012).

Pielke, R., Landsea, C., 1998. Normalized Hurricane Damages in the United States: 1925-95. Weather and Forecasting 13: 621-31.

Pielke, R., and Landsea, C., 1999. La Nina, El Nino, and Atlantic Hurricane Damages in the United States. Bulletin of the American Meteorological Society 80(10): 2027-33.

Polsky, C., Allard, J., Currit, N., Crane, R., and Yarnal, B., 2000. The Mid-Atlantic Region and its climate: past, present, and future. Climate Research 14: 161-73.

Preston, B., 2004. Observed Winter Warming of he Chesapeake Bay Estuary (1949-2002): Implications for Ecosystem Management. Environmental Management 34(1): 125-39.

Rate Inflation. http://www.rateinflation.com/ (Last accessed November 11, 2012).

Saunders, Mark A., Lea, Adam S., 2005. Seasonal prediction of hurricane activity reaching the coast of the United States. Nature 434 (7036): 1005-08.

Senkbeil, J., and Sheridan, S., 2006. A Postlandfall Hurricane Classification System for the United States. Journal of Coastal Research 22(5) 1025-34.

Shen, J., Gong, W., and Wang, H., 2006. Water level response to 1999 Hurricane Floyd in the Chesapeake Bay. Continental Shelf Research 26 (19): 2484-2502.

Shen, J., Wang, H., Sisson, M., and Wenping, G., 2006. Storm tide simulation in the Chesapeake Bay using an unstructured grid model. Estuarine, Coastal and Shelf Science 68: 1-16.

Watson, Charles C., Johnson, Mark E., 2004. Hurricane Loss Estimation Models: Opportunities for Improving the State of the Art. Bulletin of the American Meteorological Society November 2004: 1-14.

Zhang, K., Douglas, B., and Leatherman, S., 2000. Twentieth Century Storm Activity Along the U.S. East Coast. Journal of Climate 15 May, 13: 1748-61.

Appendix A

SAFFIR-SIMPSON SCALE

Category	Wind Speed	Typical Storm Surge
1	74-95 mph (62-82 knots, 119-153 km/hr)	4-5 ft. above normal
2	96-110 mph (83-95 knots, 154-177 km/hr)	6-8 ft. above normal
3	111-130 mph (96-113 kt, 178-209 km/hr)	9-12 ft. above normal
4	131-155 mph (114-135 kt, 210-249 km/hr)	13-18 ft. above normal
5	>155 mph (>135 kt, > 249 km/hr)	>18 ft. above normal

Appendix B

NWS-SED DAMAGE COST TABLE

NCDC DAMAGE CATEGORY	NCDC COST RANGE	AVERAGE USED IN STUDY
1	<$50	<$50
2	$50-$500	$275
3	$500-$5,000	$2,750
4	$5,000-$50,000	$27,500
5	$50,000-$500,000	$275,000
6	$500,000-$5,000,000	$2,750,000
7	$5 MILL-$50 MILL	$27,500,000
8	$50 MILL-$500 MILL	$275,000,000
9	$500 MILL-$500 BILL	$2,750,000,000

Appendix C

CBR STORM DAMAGE DATABASE

Year	Name	Month	Cat	Origin	Path	Killed	Injured	Total Damage Amount	SS	Flooding	Wind	OTHER	NR	DEFINING DAMAGE TYPE	Cost of SS	Cost of Flooding	Cost of Wind	Cost of Other	Cost of NR
1950-1959																			
1952	Able	9	TS	CV	LAND	1	NR	$500,000	0	15	25	60	0	OTHER: tornado	$0	$75,000	$125,000	$300,000	$0
1953	Barbara	8	1	CARI	ATL	1	1	$550,000	0	10	60	30	0	WIND	$0	$55,000	$330,000	$165,000	$0
1954	Carol	8	2	CARI	ATL	0	NR	MINIMAL	90	0	10	0	0	STORM SURGE	$0	$0	$0	$0	$0
1954	Hazel	10	ET	CARI	LAND	48	29	$75,595,000	20	10	70	0	0	WIND	$15,119,000	$7,559,500	$52,916,500	$0	$0
1955	Connie	8	TS	CV	BAY	16	NR	$5,000,000	0	20	0	80	0	OTHER: tornado	$0	$1,000,000	$0	$4,000,000	$0
1955	Diane	8	TS	CV	LAND	75	NR	$78,340,000	0	95	5	0	0	FLOOD	$0	$74,423,000	$3,917,000	$0	$0
1956	Flossy	9	ET	GULF	ATL	NR	NR	$100,000	50	50	0	0	0	STORM SURGE/ FLOODING	$50,000	$50,000	$0	$0	$0
1959	Cindy	7	TS	EAST	COASTX	NR	NR	$27,500	0	70	0	30	0	FLOOD	$0	$19,250	$0	$8,250	$0
8	STORMS							**$160,112,500**	**160**	**270**	**170**	**200**	**0**	FLOOD DECADE	$15,169,000	$83,181,750	$57,288,500	$4,473,250	$0

Year	Name	Month	Cat	Origin	Path	Killed	Injured	Total Damage Amount	SS	Flooding	Wind	OTHER	NR	DEFINING DAMAGE TYPE	Cost of SS	Cost of Flooding	Cost of Wind	Cost of Other	Cost of NR
1960-1969																			
1960	Brenda	7	TS	GULF	COASTX	45	NR	$27,500	45	45	10	0	0	STORM SURGE / FLOODING	$12,375	$12,375	$2,750	$0	$0
1960	Donna	9	2	CV	ATL	5	9	$575,000	5	35	60	0	0	WIND	$28,750	$201,250	$345,000	$0	$0
1961	Esther	9	TS	EAST	COASTX	NR	NR	NR	MIN	MIN	MIN	MIN	0	MINIMAL	$0	$0	$0	$0	$0
1965	NotNamed	6	ET	GULF	COASTX	NR	NR	NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
1967	Doria	9	TS	EAST	ATL	0	0	$27,400	50	0	50	0	0	STORM SURGE / HIGH WIND	$13,700	$0	$13,700	$0	$0
1968	Abby	6	TD	GULF	ATL	0	NR	NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
1969	Camille	8	TD	GULF	XLAND	102	109	$104,027,500	0	95	0	5	0	FLOOD	$0	$98,826,125	$0	$5,201,375	$0
7	STORMS							**$104,657,400**	**100**	**175**	**120**	**5**	**200**	VARIOUS	$54,825	$99,039,750	$361,450	$5,201,375	$0

Year	Name	Month	Cat	Origin	Path	Killed	Injured	Total Damage Amount	SS	Flooding	Wind	OTHER	NR	DEFINING DAMAGE TYPE	Cost of SS	Cost of Flooding	Cost of Wind	Cost of Other	Cost of NR
1970-1979																			
1970	Alma	5	ET	CARI	ATL	NR	NR	NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
1971	Doria	8	TS	CV	COASTX	2	1	$825,000	0	60	30	10	0	FLOOD	$0	$495,000	$247,500	$82,500	$0
1971	Ginger	10	TD	CARI	LAND			NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
1972	Agnes*	6	TS	GULF	ATL	63	NR	$2,400,000,000	0	90	5	5	0	FLOOD	$0	$2,160,000,000	$120,000,000	$120,000,000	$0
1976	Belle	8	2	EAST	ATL	1	1	$7,750	0	5	95	0	0	WIND	$0	$388	$7,363	$0	$0
1979	Bob	7	TD	GULF	LAND	NR	NR	NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
1979	David	9	TS	CV	LAND	2	41	$75,532,000	0	30	10	60	0	OTHER	$0	$22,659,600	$7,553,200	$45,319,200	$0
7	STORMS							**$2,476,364,750**	**0**	**185**	**140**	**75**	**300**	FLOOD DECADE	$0	$2,183,154,988	$127,808,063	$165,401,700	$0

Year	Name	Month	Cat	Origin	Path	Killed	Injured	Total Damage Amount	SS	Flooding	Wind	OTHER	NR	DEFINING DAMAGE TYPE	Cost of SS	Cost of Flooding	Cost of Wind	Cost of Other	Cost of NR
1980-1989																			
1981	Bret	7	TS	EAST	LAND	NR	NR	NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
1983	Dean	9	TS	EAST	LAND	0	0	$4,810	75	15	10	0	0	STORM SURGE	$3,608	$722	$481	$0	$0
1985	Danny	8	ET	CARI	LAND	0	0	$10,275,000	0	100	0	0	0	FLOOD	$0	$10,275,000	$0	$0	$0
1985	Gloria	9	2	CV	ATL	0	4	$57,750,000	30	30	40	0	0	WIND	$17,325,000	$17,325,000	$23,100,000	$0	$0
1985	Henri	9	TS	EAST	ATL	NR	NR	NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
1986	Charley	8	1	GULF	ATL	0	0	$10,027,500	50	0	50	0	0	STORM SURGE/WIND	$5,013,750	$0	$5,013,750	$0	$0
1988	Chris	8	TD	CV	LAND	0	0	$3,025,000	0	40	60	0	0	WIND	$0	$1,210,000	$1,815,000	$0	$0
7	STORMS							**$81,082,310**	**155**	**185**	**160**	**0**	**200**	WIND DECADE	$22,342,358	$28,810,722	$29,929,231	$0	$0

Year	Name	Month	Cat	Origin	Path	Killed	Injured	Total Damage Amount	SS	Flooding	Wind	OTHER	NR	DEFINING DAMAGE TYPE	Cost of SS	Cost of Flooding	Cost of Wind	Cost of Other	Cost of NR
1990-1999																			
1991	Bob	8	3	EAST	ATL	0	0	MIN	MIN	MIN	MIN	MIN	100	MINIMAL	$0	$0	$0	$0	$0
1992	Danielle	9	TS	EAST	ES	0	0	$55,000	80	20	0	0	0	STORM SURGE	$44,000	$11,000	$0	$0	$0
1994	Beryl	8	TD	GULF	LAND	1	4	$44,277,675	0	100	0	0	0	FLOOD	$0	$44,277,675	$0	$0	$0
1996	Bertha	7	TS	CV	COASTX	0	0	$615,000	0	10	45	45	0	WIND/OTHER	$0	$61,500	$276,750	$276,750	$0
1996	Fran	9	1	CV	LAND	4	1	$170,683,000	35	60	5	0	0	FLOOD	$59,739,050	$102,409,800	$8,534,150	$0	$0
1996	Josephine	10	ET	GULF	ATL	0	0	$190,000	5	50	45	0	0	FLOOD	$9,500	$95,000	$85,500	$0	$0
1997	Danny	7	TS	GULF	ATL	NR	NR	NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
1999	Dennis	9	TD	CARI	LAND	0	6	$48,864,000	60	30	10	0	0	STORM SURGE	$29,318,400	$14,659,200	$4,886,400	$0	$0
1999	Floyd	9	1	CV	ATL	8	30	$248,575,000	5	90	5	0	0	FLOOD	$12,428,750	$223,717,500	$12,428,750	$0	$0
9	STORMS							**$513,259,675**	**185**	**360**	**110**	**45**	**200**	FLOOD DECADE	$101,539,700	$385,231,675	$26,211,550	$276,750	$0

Year	Name	Month	Cat	Origin	Path	Killed	Injured	Total Damage Amount	SS	Flooding	Wind	OTHER	NR	DEFINING DAMAGE TYPE	Cost of SS	Cost of Flooding	Cost of Wind	Cost of Other	Cost of NR
2000-2006																			
2000	Gordon	9	ET	GULF	XLAND			$25,000	0	100	0	0	0	FLOOD	$0	$25,000	$0	$0	$0
2000	Helene	9	TS	CARI	ATL	NR	NR	NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
2001	Allison	6	TS	GULF	ATL	1	0	$5,000,000	0	100	0	0	0	FLOOD	$0	$5,000,000	$0	$0	$0
2003	Isabel	9	1	CV	LAND	0	0	$583,320,000	90	5	5	0	0	STORM SURGE	$524,988,000	$29,166,000	$29,166,000	$0	$0
2004	Bonnie	8	TD	CARI	ATL	NR	NR	NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
2004	Charley	8	ET	CARI	ATL	0	0	$5,000	0	0	95	5	0	WIND	$0	$0	$4,750	$250	$0
2004	Gaston	8	TS	EAST	XLAND	NR	NR	NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
2004	Ivan	9	TD	CV	XLAND	0	0	$139,900,000	0	20	45	35	0	WIND	$0	$27,980,000	$62,955,000	$48,965,000	$0
2004	Jeanne	9	ET	CARI	XLAND	0	0	$2,000,000	0	100	0	0	0	FLOOD	$0	$2,000,000	$0	$0	$0
2005	Cindy	7	ET	GULF	XLAND	0	0	$5,000	0	100	0	0	0	FLOOD	$0	$5,000	$0	$0	$0
2006	Beryl	7	TS	EAST	ATL	0	0	NR	NR	NR	NR	NR	100	NR	$0	$0	$0	$0	$0
2006	Ernesto	9	ET	CARI	LAND	0	2	$92,700,000	10	50	40	0	0	FLOOD	$9,270,000	$46,350,000	$37,080,000	$0	$0
12	STORMS							**$822,955,000**	**100**	**475**	**185**	**40**	**400**	FLOOD DECADE	$534,258,000	$110,526,000	$129,205,750	$48,965,250	$0
														SUBTOTAL=	**$673,363,883**	**$2,889,944,884**	**$370,804,544**	**$224,318,325**	**$0**
															TOTAL DAMAGE=	**$4,158,431,635**			