ESTIMATING ATLANTIC BASIN TROPICAL CYCLONE LANDFALL PROBABILITY FOR THE UNITED STATES

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ESTIMATING ATLANTIC BASIN TROPICAL CYCLONE

LANDFALL PROBABILITY FOR THE UNITED STATES

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to Alecia, Holly, and Baby B.

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A dissertation is a strange beast. There is no single formula for producing the ideal document. However, those who complete the process share many similar experiences. First and foremost is the support of friends and family. Writing is often a lonely process; it's just you and the computer. Having loved ones strategize, encourage, support, and review your work is a fulfilling and bonding experience. Initially, the research topic is fresh and exciting. After a while, the topic is not quite as exciting but the support keeps you moving along. To those who supported and encouraged me during this process, I say a collective "thank you."

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ESTIMATING ATLANTIC BASIN TROPICAL CYCLONE

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SUPERVISING PROFESSOR: RICHARD DIXON

This dissertation examines the historical record of hurricanes and tropical storms in the Atlantic Basin to determine the eventual landfall probability for the United States coastline based on the complete tracks of the storms. A spatial dimension is added so that the entire basin is evaluated to determine which storms in all portions of the basin ultimately strike the United States. A tessellation of 3,375 hexagons are systematically evaluated and eventual landfall probabilities are calculated for all storms passing through each hexagon. Probabilities are calculated and mapped for each of twelve states and regions from Texas to Maine. The maps show spatial areas that contribute storms to each of the twelve states and regions. Additionally, an average length of time until landfall is calculated for the entire Atlantic Basin based on the complete period of record. This highlights regions of the Atlantic Basin lying outside of the maximum forecast period – up to 15 days prior to potential landfall.

Key words: Hurricane, HURDAT, best track, landfall, probability, hazard, risk, GIS.

CHAPTER 1

INTRODUCTION

Hurricanes play an important role in the daily life of millions of United States residents along the coast of the Atlantic Ocean and Gulf of Mexico. The possibility of a storm potentially threatening a coastal area has substantial human and economic repercussions. Property valued in the billions of dollars can be damaged or destroyed. Natural resource extraction can be severely affected. Coastal erosion can permanently alter the landscape. Many aspects of daily life, including our personal safety, are affected by these seasonal storms. Figure 1.1 shows the geographic extent of the North Atlantic basin – the ocean region producing storms affecting the United States. The southwestern United States is occasionally affected by decaying tropical cyclones from the eastern Pacific Basin (Ludlum 1963). Those storms are not analyzed as part of this dissertation.

Once a tropical cyclone has formed, residents of coastal states have a vested interest in knowing where the storm is headed. Citizens, property owners, business owners, government officials, and others are keenly interested in the eventual path of the storm. The National Hurricane Center (NHC) is currently the United States governmental agency responsible for providing projections and predictions for storm location and intensity. Their forecasts are fundamentally similar to other weather forecasts in that the atmosphere is analyzed using the properties of fluid dynamics

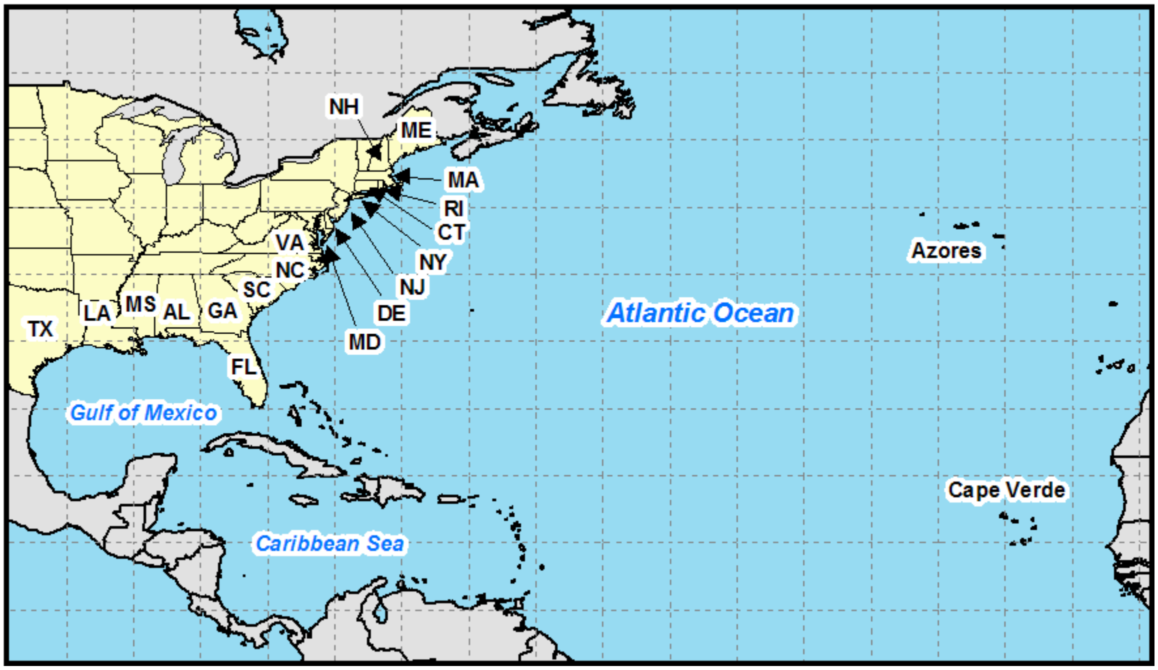


Figure 1.1 The North Atlantic tropical cyclone basin.

(Weber 2003). In addition, the NHC issues watches and warnings according to the potential impacts of a particular storm for specific regions of coastline.

Little attention is given to the climatological record when projecting the future track and strength of the storm. Only one of the NHC computer models directly uses climatology to predict future storm movement; however, several statistical models utilize climatological parameters. The "CLIPER" model (CLImatology & PERsistence), considers the historical movement of hurricanes and tropical storms in the Atlantic Basin between 1932 and 1970 to generate climatological averages based on a current position (NHC 1997). The rationale behind the "CLIPER" is analogous to daily weather forecasting. Namely, the best method for predicting what the weather will be like today at a given location is to extrapolate the previous day's conditions; this is the "persistence" method. The period 1932 to 1970 is used for comparative consistency. If climatological storm movements change over time, the stated accuracy of a model is subject to change even if the model itself is not changed due to the presence of additional storms in the database.

The second best method is to look at the historical record; i.e., if the average high temperature for a location is 20^{o} C based on some period of record, then predicting a high temperature of 20^{o} C is a reasonable guess; this is the "climatology" method. The "CLIPER" model performs better in certain regions of the Atlantic Basin than others. In general, storms at lower latitudes are best assessed by the "CLIPER" model. An update of the "CLIPER" model, called "CLIPER5," was developed to utilize a larger set of data (NHC 2006g). The forecast errors are similar to "CLIPER" but the forecast biases are smaller.

The National Hurricane Center has collected 150+ years of tropical cyclone data for the Atlantic Ocean and Gulf of Mexico (NHC 2005). Over 37,000 storm observations exist in the data set but little research has been conducted using this important data set. The purpose of this research project is twofold. First, to determine if there are significant or meaningful spatial patterns in the climatological record of Atlantic Basin hurricanes? Second, to determine if probability maps can be developed to indicate the relative likelihood of landfall as a function of storm position?

Whenever a storm is active, coastal residents want to know where the storm is headed. This dissertation intends to take a step back and find out where storms have historically traversed. If, for example, a hurricane is very near the island of Bermuda, residents of southern Texas probably have little to worry about. Even without analyzing the NHC forecasts, most people who regularly follow tropical cyclones *know* that storms *never* move from Bermuda towards southern Texas. This type of *ad hoc* analysis is based on anecdotal climatology. Conversely, those same residents of southern Texas would be very concerned if told that a hurricane existed near the Mexican island of Cozumel or Havana, Cuba. Why would they be so concerned? Residents of southern Texas *know* that hurricanes come through the Yucatan Channel. Again, the anecdotal climatology tells them so. Part of this lay person knowledge is strictly a function of proximity. One would be very concerned about a major hurricane 200 miles away regardless of which way it was moving.

At what point does local knowledge begin to loose its effectiveness? The southern Texas resident who is concerned about a hurricane near Cozumel may not be very concerned about a storm near Puerto Rico for several reasons. First and foremost is the increased distance. Puerto Rico is much farther away from southern Texas than is Cozumel and any storm would take several more days to arrive even if it were on a direct course for a specific location. This increased distance away from a potential landfall also increases the likelihood of the storm going in some other direction. What if the same resident had a probabilistic analysis of the climatological record at their fingertips? That analysis might show that their location has a 15% historical chance of eventually being struck by a hurricane that is near Puerto Rico. The same analysis may also show that there is a 12% historical chance of eventually being struck by a hurricane that is near Havana, Cuba. How would this affect the local response?

There are potentially many new probabilistic relationships in the historical data that might aid the public in preparing for these destructive storms. Most importantly, emergency management officials can utilize this information so that they may gather resources, direct personnel, and initiate evacuation planning when a storm enters a particular location. Currently, the National Hurricane Center (NHC) issues forecasts up to 5 days (120 hours) in advance (NHC 2006c). If a storm is moving at 10 knots, up to 1,200 nautical miles (nm) of storm movement is potentially forecastable. What if a storm is 2,000 nautical miles away from possible impact to the U.S. coastline? What if a storm were half-way between the Lesser Antilles and the west coast of Africa? The climatological record would indicate that certain coastal areas should be more concerned than others.

Part of this study will evaluate how the climatological record compared to the actual track of the land falling major hurricanes of 2005 (Dennis, Katrina, Rita, and Wilma). Were the areas that were ultimately impacted shown to be within the areas of highest historical probabilities? If so, at what time frame? The NHC assesses each storm for forecast accuracy once the storm's life cycle is complete. How did this compare to the climatological expectation? Were the 2005 storms historically representative? Ultimately, the knowledge of where tropical cyclones typically move will aid those people who make decisions regarding public safety and public policy.

The danger in using the climatological record for estimating landfall probability should not be disregarded. Even though storms that pass near Bermuda have never struck southern Texas doesn't mean that it will not happen in the future. Probability only analyzes events that have occurred in the past and extrapolates those relationships to the future. The danger in this is either worrying too much when there is nothing to worry about or worrying too little when there is much to worry about. Meteorological forecasts always take precedent when assessing a storm. However, a climatological perspective will significantly help assess the historical risk of a location.

Climatology is often a common-sense, reality check for meteorology. If, for example, the weather forecast for a city predicted a high temperature of 30^{o} C when the normal high temperature for that city is 20^{o} C and the record high temperature is 25^{o} C, then the validity of that forecast must be questioned. Computer models frequently lose perspective on what is most likely given the climate history of a region. Sometimes the human forecaster must modify computer ensemble forecasts based on their local knowledge of a region. The local knowledge of a region is essentially the anecdotal climatology of that region. Ideally, this same anecdotal knowledge now quantified by the results of this study will not only aid the general public, but also help the forecaster in their storm projections.

Until this point, the discussion has centered around future storm location as a function of distance and direction. Tropical cyclone intensity is also measured as part of the hurricane climate record. Each storm position has an associated wind speed. Analysis of these wind speeds allows for a climatological pattern to be developed for the different regions of the Atlantic Basin. As with location projections, intensity forecasts have significant impacts on storm preparedness activities. Many individuals will "ride out" a modestly intense storm and only evacuate for the "big one" (Pielke and Pielke 1997; Fitzpatrick 2005).

Certain regions in the Atlantic Basin are historically conducive to storm intensification. Other regions inhibit storm intensification. Knowledge about where these regions exist will aid forecasters and the public. For example, anecdotal evidence suggests that tropical cyclones in the Gulf of Mexico intensify as they pass over the Loop Current. This study intends to remove many of the anecdotal aspects to hurricane and tropical storm climatology and assign them a quantitative value.

Development of probability maps will benefit the study and understanding of tropical cyclones. The Spanish philosopher, Santayana, wrote, "those who fail to learn the lessons of history are doomed to repeat it." This statement is especially important in regards to hurricane analysis. Hurricanes like Camille, Andrew, and Katrina, were inevitabilities; but how probable were they? When will the next "big one" strike a particular region and where should those residents look for that storm to come from? Climatology will never be substituted for real-time forecasts but should also never be ignored.

All measurement parameters in this document relating to storm movement and intensity are reported in English units to follow NHC conventions. A metric conversion table is provided in Appendix A.

CHAPTER 2

LITERATURE REVIEW

Tropical Cyclones

For the purpose of this study, a tropical cyclone is an area of low pressure whose energy is derived from changes in the state of water vapor and whose wind speeds are greater than or equal to 35 nautical miles per hour (knots) (Cline 1926; Tannehill 1945; NOAA 2006). There are specific atmospheric processes that distinguish a tropical cyclone from a non-tropical cyclone; these differences are related to the thermal properties of the storm (Dunn and Miller 1960; Stull 2000). The energy source for non-tropical cyclones is the change in temperature with altitude. Tropical cyclones derive their energy from the evaporation of warm ocean waters and eventual condensation of the water vapor. If the availability of warm water (>80^{o} F) is absent, a new tropical cyclone cannot form and an existing tropical cyclone will weaken (Stull 2000).

The strength of a tropical cyclone is described by specific categories related to the wind speed. A "tropical storm" is a specific type of tropical cyclone containing wind speeds of at least 35 knots but less than 65 knots. A storm with winds at least 65 knots is called a "hurricane" (Stull 2000). With the "hurricane" category, there are five levels of intensity that are described by Saffir and Simpson (NOAA 2006) – Category 1 is the weakest and Category 5 is the strongest. For this study, tropical cyclones are not broken down by intensity. The probability of storm movement is treated independently of storm strength.

Hurricanes Over Time

Throughout the entire recorded history of the western Atlantic Ocean, hurricanes have occurred (Cline 1926; Dunn and Miller 1960; Ludlum 1963; Helm 1967; Simpson 1981; Lauber 1996). In fact, these great storms affected the expeditions of Christopher Columbus in the late 15^{th} century (Ludlum 1963). The Spaniards called these storms “huracáns” after the native Indian words “huiranvucán,” “aracán,” and “uricán” (Helm 1967). Unfortunately, the significance of hurricanes to humans over the centuries is highly correlated to the number of deaths. Once reliable instruments were developed, a storm’s strength (wind speed or barometric pressure) could be quantified as a separate measurement of intensity. The relationship between storm intensity and storm destructiveness is not always straightforward. However, knowing the patterns of tropical cyclone tracks is important in vulnerability assessment and mitigation.

The occurrence of these storms has influenced settlement patterns and affected numerous governmental policies (Pielke and Pielke 1997). Unfortunately, history tends to repeat itself given a long enough recurrence interval. For example, after sustaining two direct hits from hurricanes, the town of Indianola, Texas, decided not to rebuild (Bomar 1995) and today exists only as a park. Understanding where and when tropical cyclones move over time greatly enhances the planning, response, and mitigation strategies local, regional, and national governments utilize.

Hurricane Frequency and Movement

The total number or tropical cyclones in the North Atlantic varies from year to year. In 2005, 28 storms reached tropical storm intensity or greater while only 4 such storms formed in 1983; the long term average is 9.7 per year (AOML 2005). More than 1,300 storms are recorded in the HURDAT data set (NHC 2005). Even though some years are more active than others, there is a sufficiently large sample to draw probabilistic conclusions. Figure 2.1 is a map of all tropical cyclone tracks between 1851 and 2004; Figure 2.2 maps all tropical cyclone tracks in the Gulf of Mexico during the same period.

Several factors affect the movement of storms in the North Atlantic Basin (Tannehill 1945). First and foremost are the positions of upper level winds. These wind regimes are a function of the position of the dominant high pressure cell in the sub-tropical North Atlantic, the "Azores High." The clockwise winds around this anticyclones force most storms to move from east to west when they are south of the anticyclone. When storms approach the southwestern portion of the subtropical high pressure cell, they usually turn to the northwest, then north, and eventually northeast. A number of storms south of this Azores High begin their recurvature before ever reaching the same longitude as the Lesser Antilles. The geographical extent and strength of the high pressure cell ultimately determines the future path of storms in the North Atlantic Basin. Even though the positions of this high pressure cell changes little from day to day, relatively minor positional fluctuations greatly affect storm tracks. When looking at maps with many storm tracks overlaid, this pattern is evident (see Figures 2.1 and 2.2). Tropical cyclones in the eastern and central Atlantic almost always travel between due west and west-northwest. In the area of the Greater Antilles, storms generally travel

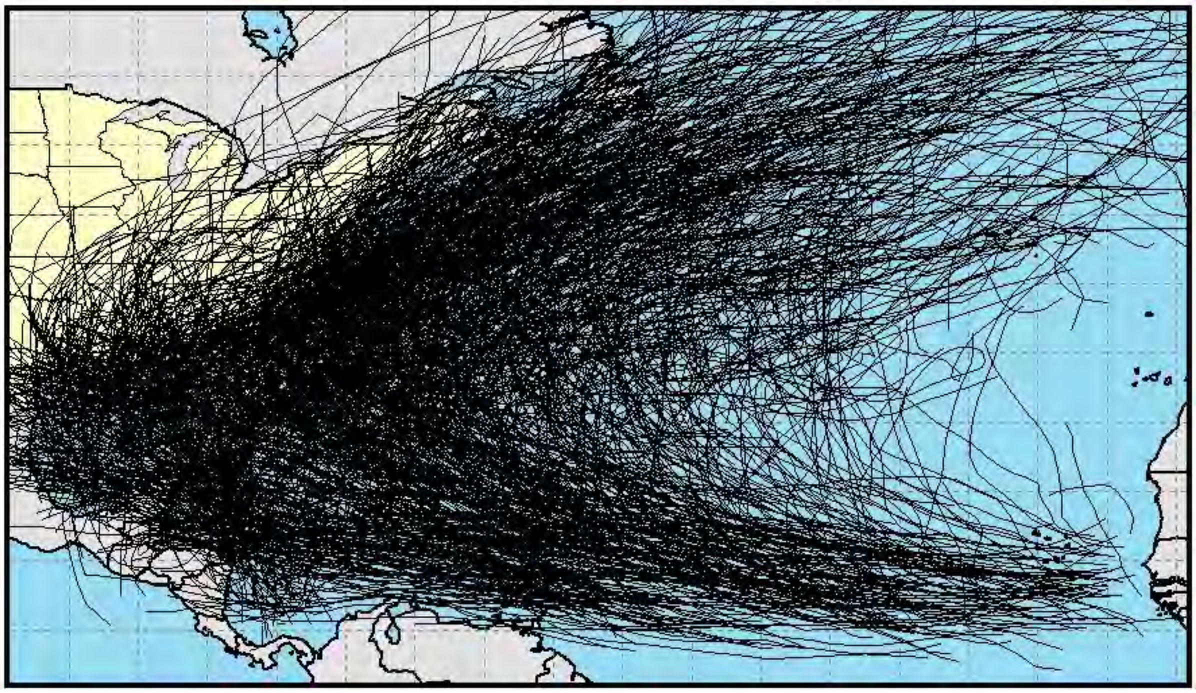


Figure 2.1 All tropical cyclone tracks between 1851 and 2004 in the entire North Atlantic Basin.

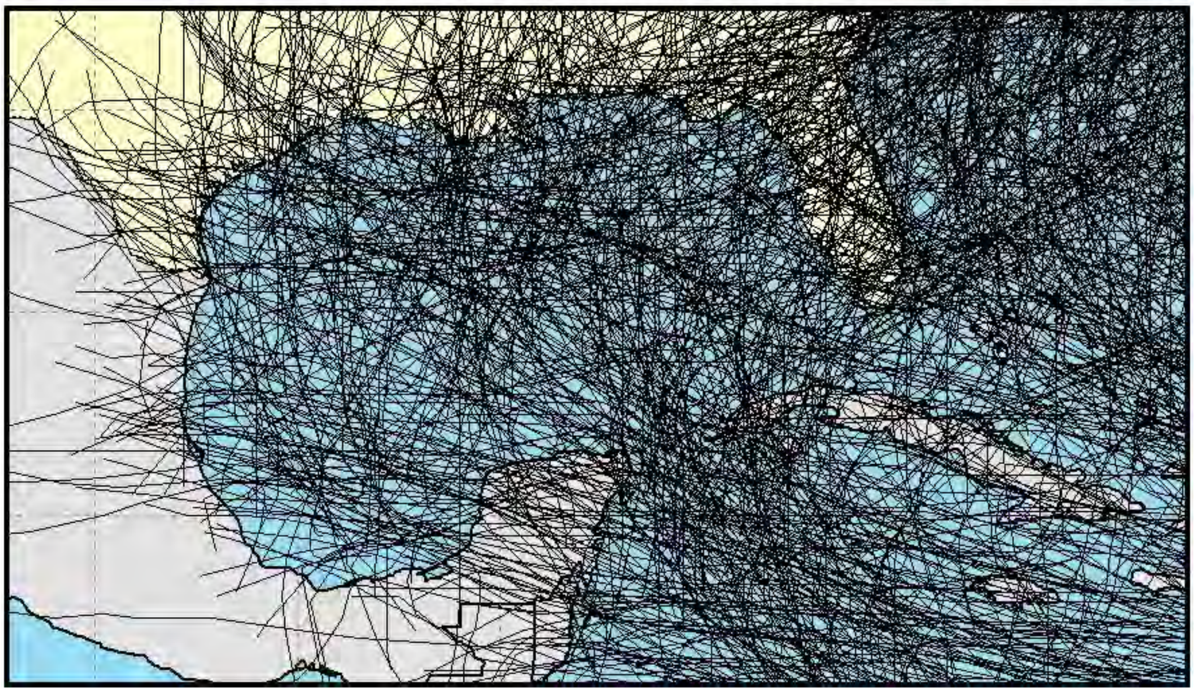


Figure 2.2 All tropical cyclone tracks between 1851 and 2004 in the Gulf of Mexico.

northwest. Along the East Coast of the U.S., most storms travel in a northerly or north north-westerly direction. Of course these are only verbal descriptions and many variations exist for individual storms. One of the goals of this dissertation is to add a quantitative dimension to these verbal descriptions.

Hurricane Forecasting

The National Hurricane Center is the governmental agency responsible for issuing official forecasts, watches, and warnings (NHC 2006a). The NHC issues forecasts every six hours for a named storm. If landfall is imminent, intermediate advisories are issued but these are not included in the HURDAT database. Every official forecast lists a predicted location and estimated intensity for one to five days in the future (NHC 2006c). The current position and all forecast positions are reported in latitude and longitude coordinates using one place after the decimal. This translates to a positional precision of 4.5 to 6.5 nautical miles depending on latitude. All wind speeds are reported in knots and are rounded to the nearest 5 knots. Appendix A contains a conversion table of English and metric units for wind speeds, distances, and temperatures.

One measure of forecast accuracy is the "mean forecast error." This measures the average positional and intensity difference between the forecast and the observation (NHC 2006b); i.e., in hindsight, how accurate the forecasts were. For the 5-year period ending in 2005, the 24-hour mean forecast error for all North Atlantic storms was 64.5 nautical miles; the mean error in intensity was 9.8 knots (NHC 2006b). The distance error is not directional, therefore, if a storm is 24 hours from the coast, a 130 nautical mile segment of coastline is potentially at risk (assuming that the storm is moving perpendicular to the coast). The five day (120 hour) locational forecast error is 303 nautical miles. The intensity error is 21.8 knots (NHC 2006b). As large as these forecast errors seem, they are less than purely climatological averages. If this is the case, why does climatology matter? The simple answer is that the forecasters and the computer models all take climatology into account. They benefit from atmospheric models and history. Climatology also allows an estimation of a storm's future movement beyond the time frame of the official forecast (>5 days). This benefit is explored in greater detail in chapters 4 and 5.

Probability

The simplest measure of the likelihood of an event occurring is to know how many times in the past (if any) that event occurred (Lucas 1970). The probability of an event is "the ratio of the number of times the event occurs to the total number of opportunities for occurrence of the event" (Kachigan 1991, 57). There are two methods for estimating probability, theoretical (*a priori*) and empirical (*a posteriori*). The theoretical approach involves no firsthand knowledge of past events. The empirical approach is based on repeated observations of events over some period of time (Kachigan 1991). In the case of tropical cyclones, a theoretical probability of landfall for a particular region is derived from data on prevailing wind patterns, sea surface temperatures, and other climatological variables that influence tropical systems. The empirical approach looks at where storms tracked in the past to generate frequency tables for different locations. This dissertation utilizes the empirical probability approach to assess the relative likelihood of movement of tropical storms and hurricanes.

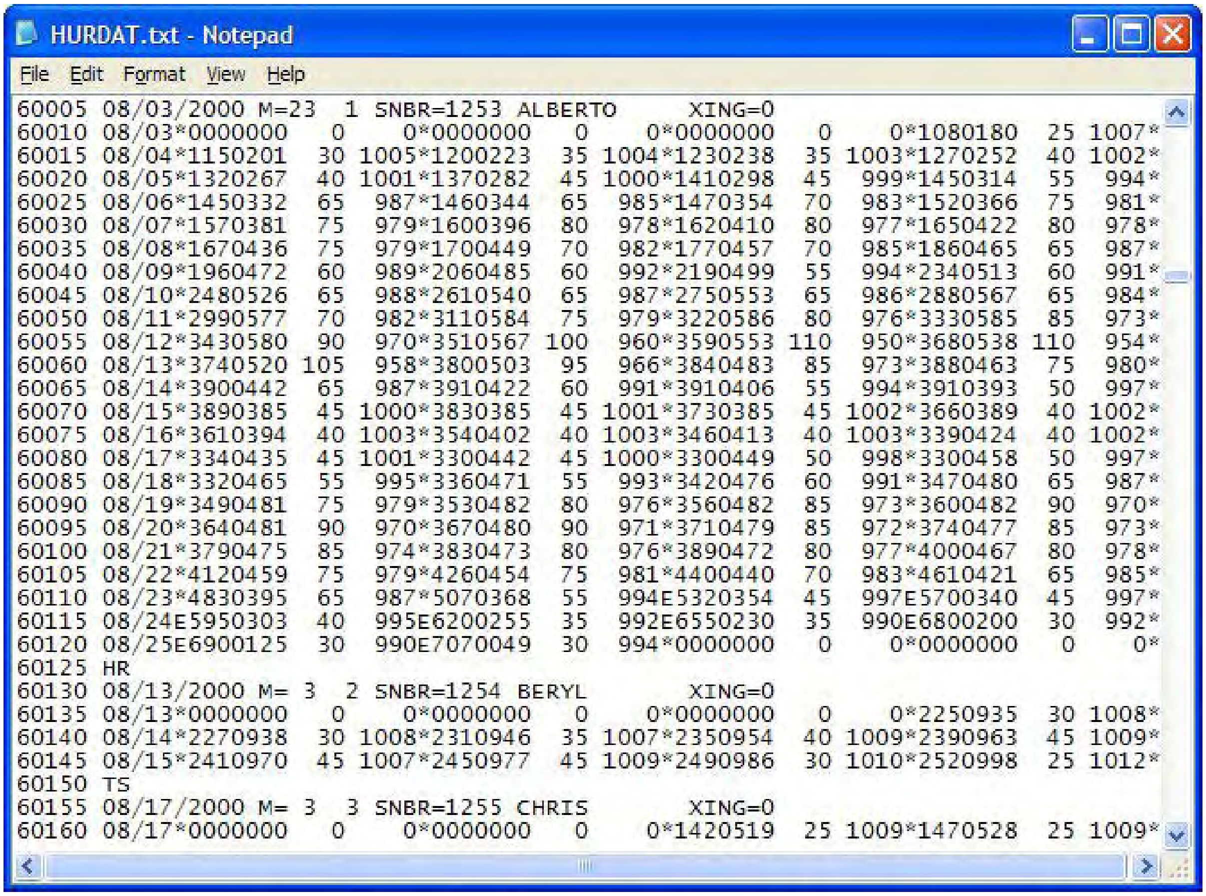
Hurricane Probability Studies

Almost every book on tropical cyclones contains a series of storm track maps. Why is this? A nearly implicit expectation of pattern recognition exists in those storm tracks. The reader is left to make judgments as to what the jumbled sets of lines actually mean. Is there a pattern within those tracks? The professional and research communities recently began analyzing the historical storm tracks in an attempt to decipher trends and develop a comprehensive tropical climatology for the Atlantic Basin. The breadth of this research is not as comprehensive as one might expect. More specifically, landfall probability studies looking out to the ocean to determine where storms originate are relatively uncommon. This literature review will discuss the relevant works involving hurricane climatology and probability studies.

HURDAT Data Set

The basis for analytical research on hurricane climatology is the HURDAT data set published by the National Hurricane Center (NHC 2005). This data set contains position and intensity information for all known storms in the Atlantic Basin from 1851 through the present. A data point is established 4 times per day (every six hours) for each storm. When only sporadic information is available, a "best guess" is used to interpolate positions so that the data set is continuous (Jarvinen, Neumann, and Davis 1984). Gaps are "filled-in" using hurricane climatology; i.e., prior knowledge about how hurricanes move and intensify. Each position in the HURDAT data set contains a latitude coordinate, longitude coordinate, and estimated wind speed. The latitude and longitude coordinates use one decimal place corresponding to an accuracy of 4.5 to 6.5 nautical miles. The wind speeds are rounded to the nearest 5 knots. Some of the storms contain pressure observations at specific points (usually at landfall). However, this information is sparse prior to the 1970s and nearly non-existent prior to the 1950s. Since measurements are recoded every six hours, along with an estimated wind speed, a temporal and intensity continuity exists in the data set enabling comparisons between storms. Figure 2.3 shows a sample section of the HURDAT data file for Hurricane Alberto in the year 2000.

Tropical cyclone data collected prior to the advent of reconnaissance aircraft (1943) and weather satellites (1960) is somewhat suspect. Ship reports and damage reports for landfalling storms were the only methods of collecting storm information. For storms in the HURDAT data file that occurred before 1911, the average positional error is +/-100 nautical miles. The average intensity error is +/- 20 knots (Landsea et al. 2004). Therefore, caveats must be presented to any potential users of these data. The HURDAT data set is also referred to as the "Best Track" data set; although there are no tracks at all in a literal sense. The data set is only a sequence of points with an implied line connecting those points. The data are intentionally smoothed to remove small variations in the storm's movement. Also, the track represents the line where the highest winds occurred (Jarvinen, Neumann, and Davis 1984). This track of maximum wind intensity does not always correspond to the location of the eye or circulation center. An example is Hurricane Carla in 1961. Carla's Best Track coordinates are nearly 100 miles north of the storm center as measured by radar. The reason is that the storm's forward motion and external factors caused the maximum winds to be offset from the actual center (Jarvinen, Neumann, and Davis 1984). Therefore, the HURDAT data set is not ideal for modeling storm surges or other issues requiring precise locational information. However, since the



HURDAT.txt - Notepad

File Edit Format View Help

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60015 08/04*1150201  30 1005*1200223  35 1004*1230238  35 1003*1270252  40 1002*
60020 08/05*1320267  40 1001*1370282  45 1000*1410298  45  999*1450314  55  994*
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60035 08/08*1670436  75  979*1700449  70  982*1770457  70  985*1860465  65  987*
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Figure 2.3 A portion of the raw HURDAT file. Each line contains four position, wind, and pressure points.

area of maximum winds is effectively the center of strength, the limitation to the data set is not significant to this dissertation.

NOAA Technical Papers on Hurricane Probability

The most in-depth, analytical studies of hurricane track climatology were produced by the staff of the National Oceanic and Atmospheric Administration (NOAA). These studies were primarily conducted during the 1960s and 1970s when analytical capabilities were limited by computer power.

The first of these studies undertaken (Cry 1965) primarily showed tropical cyclone tracks and their eventual landfall. Summaries of landfall statistics are presented for the entire coastline. The published results describe, for example, what the landfall probability for a specific region is during a given hurricane season. Landfall probability is easily derived by dividing the number of total storms by the period of record; although a smoothing function would yield more consistent results. Cry systematically mapped all tropical cyclone tracks between 1876 and 1963. These maps ultimately were the basis for the HURDAT data set (Jarvinen, Neumann, and Davis 1984).

A spatial probability study released in 1971 (Hope and Neumann 1971) contained the first maps of storm tracks and calculated probabilities of eventual landfall for a given location. The authors divided the entire Atlantic Basin into 2.5^o x 2.5^o squares. For each square that intersected the coastline, all landfalling storms were identified. Then, each of 2.5^o x 2.5^o squares that the storm previously passed through were noted. A summation of those squares yields a relative likelihood of eventual land-fall along the previously identified section of coastline. For example, if 20 storms made landfall in the 2.5^o x 2.5^o square in southern Texas and of those 20, 14 passed through the 2.5^o x 2.5^o square immediately to the southwest, then that square has a 70% likelihood (0.7 probability) of contributing a storm to the southern Texas coast. The authors performed this analysis along the entire coast looking at all tropical storms and hurricanes. Elsner and Kara (1999) studied only hurricane landfall probability (excluding tropical storms) using the same methodology.

Methodologically, the studies by Hope and Neumann (1971) and Elsner and Kara (1999) suffer from several limitations and differ from this dissertation in important ways. First, 2.5^{o} x 2.5^{o} squares are not all the same size. A 2.5^{o} x 2.5^{o} square between 15^{o} and 17.5^{o} north latitude covers an earth area of approximately 21,872 nm^2. A 2.5^{o} x 2.5^{o} square between 30^{o} and 32.5^{o} north latitude covers an earth area of approximately 19,476 nm^2. Therefore, the square at the lower latitude is 12% larger in area. Additionally, using a square disproportionately selects storm tracts that cross a corner of the square. The corner of a square is 1.77^{o} from the center, while the edge of the square due east, west, north, or south of the center is only 1.25^{o} away. This will over represent storms further away from the center of the square.

Ho, Schwerdt, and Goodyear (1975) address the over representation of corners by using octagons instead of squares – the octagons are 2.5^{o} x 2.5^{o} in size but with the corners shaved off. This shape closely resembles the ideal shape, which is a circle. Programmatically, an octagon is easier to write conditional queries for than a circle. Given the computational limitations of the 1970s, it is not surprising that the octagon was viewed as a reasonably close approximation of a circle. As with the earlier studies that used a 2.5^{o} x 2.5^{o} square, the octagon does not address the issue of size differences according to latitudinal changes.

Each of these studies measures a “strike” by whether a storm eventually enters a 2.5^o x 2.5^o square that overlays the coast. Political and geographical boundaries do not adhere to latitude/longitude squares. The coastline does not arbitrarily end when it reaches a certain longitude nor does a national or state boundary. Therefore, practical issues arise when interpolating from this coarse scale of analysis.

Other Research on Hurricane Probability

The research most resembling this dissertation involves a study of historical hurricane tracks and compares those tracks to a model generated series of tracks (Emanuel et al. 2006a, 2006b). The paper uses the HURDAT data set as a control variable for validating the hypothetical tracks generated by their model. The authors assume that if randomly generated hurricane tracks are similar to actual hurricane tracks, the model is successful. Once hypothetical hurricanes are successfully simulated, disaster plans, evacuation orders, etc. can be initiated. Their model produced statistically significant results; i.e., the model generated hypothetical storms that generally followed paths of historical storms in those regions. This study utilizes the HURDAT Best-Track data more than any other study published to date. However, nowhere in the paper are probability distributions delineated or average values mapped.

A similar study uses the HURDAT data set to initialize and evaluate model generated hurricanes (Vickery, Skerlj, and Twisdale 2000). The authors generated hurricanes over a 20,000 year period and assessed the relative likelihood of landfall at all coastal locations. Like the previous study, the HURDAT data set is not evaluated directly, instead, it is used to validate these model storms. In addition, the study only evaluates a static portion of the coastline and does not look backward to where the storms originated from. As mentioned earlier, hurricanes originate from other places and the geographical depth of analysis within the study is only linear. This dissertation will expand the area of probability analysis from 1-dimensions to 2-dimensions.

The only study explicitly analyzing the HURDAT data set to assess long-term averages was by Emanuel (2000). Specifically, Emanuel was interested in evaluating intensity changes during the life-cycle of a storm. The author successfully averaged historical wind speeds for the period of record to create a hypothetical wind progression. The only geographic variable was the entire basin the storm resided in (Atlantic or Northeastern Pacific). Spatially, this study was very limited. Assuming an entire basin contains homogonous conditions will lead to suspect results if any interpolation is attempted.

Other Hurricane Probability Studies

Maps showing typical movement of hurricanes and tropical storms are not uncommon. Usually, this information is conveyed through a series of large arrows and is highly subjective (NHC 2006d). As stated in the introduction section, a well-defined understanding exists regarding the movement of tropical cyclones but quantified measurements are uncommon regarding the complete storm tracks. Tannehill (1945) published maps derived from data compiled by Mitchell (1924) in his well known book on hurricanes showing average direction of movement and speed for tropical cyclones. These maps are separated by month – June, August, and October. Tannehill also provides verbal descriptions of storm movements. For example, he states “of the July storms which enter the Caribbean Sea from the east, those which pass south of Haiti eventually reach the Mexican Gulf coast west of Florida" (Tannehill 1945, 55). No quantifiable reason for this assessment is given other than the author's personal expertise.

The data Mitchell compiled was used by other authors to summarize hurricane movements (Colon 1953). Colon used 5^{o} summary data to generate contour maps of tropical cyclone speed and direction. These maps were broken down by month for the entire hurricane season. In addition, at each 5^{o} grid point, a wind rose was presented showing relative frequencies of storm movements using a 16-point compass. Colon's analysis represents the closest approximation to the goal of this dissertation; namely, a spatially subdivided, quantitative mapping analysis of storm movement and distribution. However, Colon did not attempt to measure tropical cyclone landfall, and the resolution of his analysis (5^{o}) is significantly coarser than the NOAA technical paper studies described in the earlier section.

Alaka utilized Colon's data to generate hurricane frequency maps (Alaka 1968). His report mapped each month of the year showing the frequency of occurrence for tropical cyclones, with contour lines to delineate frequency classes. While most authors are content to show numerous storm tracks so that the reader may infer general movements (Dunn and Miller 1960; Cry 1965; Ho et al. 1987; Jagger, Elsner, and Niu 2001), Alaka explicitly decided to remove subjectiveness from the process. He stated that "when paths of individual tropical storms, occurring over many years, are plotted on a chart, as was done by Tannehill and others, there results a hopelessly tangled skein with no noticeable pattern" (Alaka 1968, 10).

Several publications produce summaries of storm movement and intensity at the time of landfall based on geographic position along the coast using a milepost system analogous to a highway grid (Schwerdt, Ho, and Watkins 1979; Ho et al. 1987; Jagger, Elsner, and Niu 2001). Each of these studies partitions the coastline into 100 mile segments. The segments are analyzed and tables of hurricane climatology are generated. This implicitly assumes that different geographic regions experience different types of storms. However, the milepost system is only somewhat better than the 2.5^o x 2.5^o squares described earlier and suffers from the same limitation of spatial resolution.

Within NOAA, the unquestionable leader in quantitative, spatial hurricane climatology analysis is Charlie Neumann. Perhaps his most significant work involved separating the Atlantic Basin into 2.5^o x 2.5^o points of analysis (Neumann and Pryslak 1981). Each of the points are individually analyzed for storm movement within a certain distance of that point. The end result is a map of tightly spaced arrows whose size and orientation reflect the average storm movement. Additionally, the maps are subdivided into each month of the hurricane season. Two maps are generated for each month. The first map shows storm movement arrows. The second map contains contoured regions of the Atlantic Basin showing cumulative tropical cyclone frequencies. The analysis is performed by reviewing the HURDAT data set and letting a computer perform the calculations. This study, by using points instead of boxes, eliminates the issue of corner over-representation. However, as with the previous studies, the issue size differences between the 2.5^o x 2.5^o squares was not resolved. Additionally, no information is provided describing the methods for performing the calculations.

Hurricane Vulnerability

What is vulnerability? Researchers spend considerable energy debating this question. For the purpose of this dissertation, vulnerability is defined as the intersection of risk and exposure (Pielke and Pielke 1997). According to this definition, much of what constitutes vulnerability (the exposure portion) exists before a storm (or some other event) actually impacts a location. The risk portion of vulnerability is the historical likelihood of a storm impacting a particular region. Therefore, knowing the frequency of such events is useful for mitigating the vulnerability of a location.

Hurricane vulnerability is a frequently studied subject (Pielke and Pielke 1997; Dixon and Fitzsimons 2001; Pielke 2003; Herbert, Dixon, and Isom 2005). Maps and tables are often presented showing the frequency of tropical cyclones with population and current or inflation adjusted property values (Pielke and Pielke 1997; Dixon and Fitzsimons 2001). These measures describe the vulnerability over a relatively long period of time. On shorter time scales, an important factor in vulnerability is forecast margin of error. If a storm is heading north toward Pensacola, Florida, is there any added vulnerability for Galveston? Carter (1983) discusses the influence of forecast uncertainty on regional vulnerability when a storm is actually in progress.

CHAPTER 3

METHODS

The HURDAT data set is not perfect but is nevertheless consistent. Every storm contains a continuous sequence of points with an associated wind speed. Therefore, a systematic analysis of those positions and wind speeds is possible. Another common factor among all storms in the data set is they attained a maximum strength of at least 35 knots at some point in their history. If a storm never reached 35+ knots (i.e., it peaked at tropical depression strength), it was omitted from the database. For example, in 2005, Tropical Depression 10 (TD#10) peaked at 30 knots, so it is not included in the database. However, for all storms in the database, positions are included for the portion of the storm's life cycle where the wind speed was less than 35 knots. For example, the first three observations of hurricane Katrina in 2005 have wind speeds of 30 knots; of course, the winds later became much stronger. Many storms prior to the 1950s contain few, if any, points at tropical depression strength since remote sensing data and aerial reconnaissance data were not available. The points at tropical depression strength before the 1950s are generally over land during the decaying portion of the storm's life cycle.

The methodological goal of this dissertation is to define a discrete number of observation locations and assess the historical likelihood of storms passing within a certain distance of that observation location. Assuming the sample size is large enough and the density of measurement locations is fine enough, a comprehensive understanding of storm movement is obtainable. Unfortunately, no one measurement technique or shape is perfectly suited for conducting this type of analysis – each contains limitations and compromises.

Measurement Shapes

Several studies described previously utilize measurement areas based on rectangular coordinates; i.e., latitude and longitude (Hope and Neumann 1971; Ho, Schwerdt, and Goodyear 1975; Elsner and Kara 1999). Since tropical cyclone positions are reported in latitude and longitude, defining an observation site using rectangular coordinates is somewhat logical. However, as mentioned earlier, using shapes defined by spherical coordinates results in study areas of different sizes.

There are several useful geometric shapes for evaluating tropical cyclones over time. Figure 3.1 shows an example of several shapes. Each shape has advantages and disadvantages. The first shape is a square – used by Hope and Neumann (1971) and Elsner and Kara (1999). The spherical coordinate system issue notwithstanding, a square disproportionately represents storms passing through the corners. If the minimum distance to the edges of a perfect square are 1X units, the corners of the square are 1.4X units away. Therefore, the corners are over represented. In addition, the orientation of the square and/or the orientation of the prevailing storm tracks in the vicinity of the square will affect the measured number of storms passing through the square. As stated earlier, the sizes of the squares also change with latitude. A 1^{o} x 1^{o} square at 10^{o}N is 3,585 nm^{2}. A 1^{o} x 1^{o} square at 40^{o}N is 2,772 nm^{2}. Another shape used in the literature is an octagon (Ho, Schwerdt, and Goodyear 1975). This shape partially addresses the addresses the corner representation issue but creates several other issues. A 1^{o} x 1^{o}

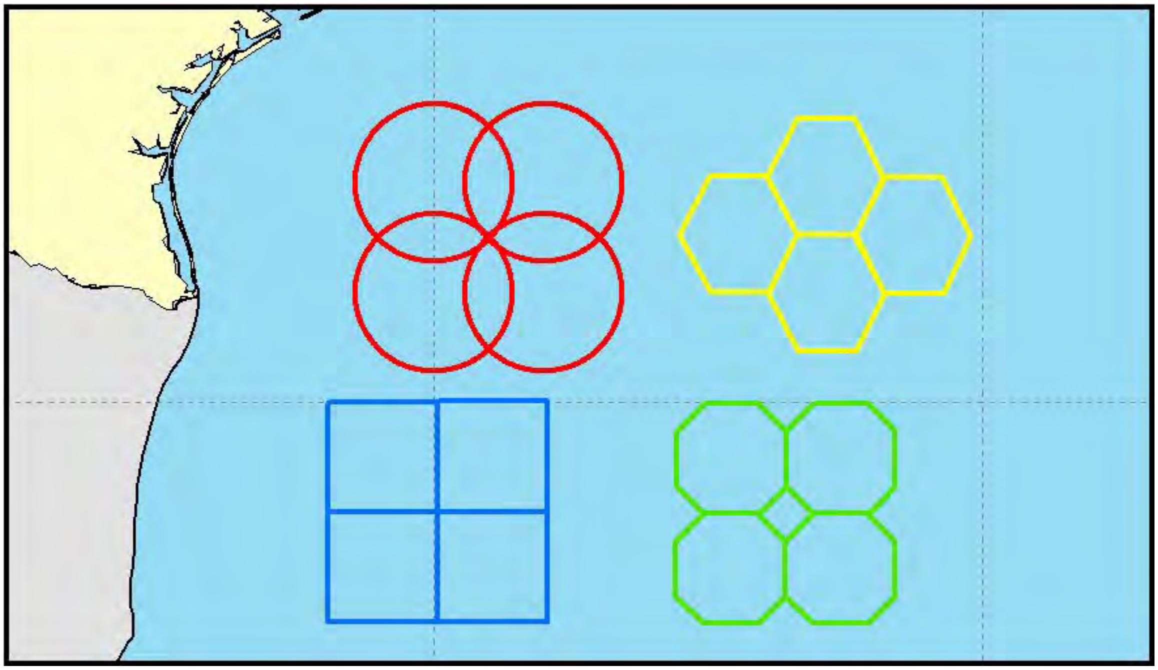

Figure 3.1 Sample map showing various options for measurement shapes (overlapping circles, hexagons, squares, and octagons) to assess historical tropical cyclone movement and landfall.

octagon at 10°N is 3,137 nm^2. A 1° x 1° octagon at 40°N is 2,425 nm^2. These areas represent 87.5% of the area of the squares. The remaining area is unaccounted for. A diamond shaped gap exists at the intersection of four octagons (see Figure 3.1). Ideally, the entire basin should be covered by the mosaic of shapes. However, the missing corners collectively represent 1/8th of the entire Basin area.

The square and the octagon are the only two shapes discussed in the literature; however, other shapes exist. In some respects, a circle represents the ideal shape, especially for studying a single location in the Atlantic Basin. A circle with a fixed radius does not suffer from the corner over representation issues that the square suffers from. The circle does contain some important limitations. For example, if the entire basin is covered by circles, there must be some amount of overlap. At 10°N, the radius of each circle must be 42 nm (total area is 5,542 nm^2). At 40°N, the radius of each circle must be 37.5 nm (total area is 4,418 nm^2). These radii ensure the least amount of overlap. However, using circles with different geographic sizes makes comparisons of results difficult. If the points are spaced father apart as latitude increases, then the radius of the circles, and therefore their areas, will remain constant. No methodology enables a network of circles to simultaneously contain no overlap and cover the entire basin - a compromise must be made. If a decision is made that no overlap is desirable and that adjoining circles will only touch each other, 21.5% of the basin will be uncovered.

The only geometric shapes that can completely cover the Atlantic Basin without any overlap are the square, triangle, and hexagon. The square, discussed earlier, is primarily limited by the corner representation issue. A network of triangles magnifies the corner issue and also magnifies the orientation issue; that is, the direction the triangle "points" affects the number of storm tracks observed intersecting the triangle.

A hexagon represents the best compromise between overlap and uniformity. As with the square and triangle, a tessellation of hexagons fits together with no area uncovered. The hexagon is a distinguished shape in the field of geography. The most famous theory in the discipline, Central Place Theory, involves hexagonal networks for describing economic relationships (Christaller 1933). Since all interior angles of the hexagon are equal and all sides are of equal length, the hexagon best approximates the ideal shape of a circle. A hexagon whose maximum extent is 1^o x 1^o at 10^oN is 2,689 nm^2. A hexagon whose maximum extent is 1^o x 1^o at 40^oN is 2,079 nm^2. The number of storms intersecting a hexagon is less dependent on the orientation of the hexagon than is the case for the square or triangle. For the above stated reasons, this dissertation utilizes hexagons as the measurement shape for analysis.

Creating Equal Area Hexagons

Due to the convergence of meridians at the poles, using rectangular coordinates to define measurement areas results in shapes of differing spatial extents. Several options are available to resolve this problem (Kimerling, Sahr, and White 1999). Spherical harmonics is one method for transforming spherical coordinates to planar coordinates for atmospheric calculations (Moses 1974). This requires sophisticated integral calculus and is unnecessarily complicated for the needs of this dissertation. To solve the map distortion (spherical coordinates) problem, the Atlantic Basin was temporarily converted from latitude/longitude coordinates to a cylindrical equal-area projection using GIS. As the name implies, an equal area projection is specifically designed to eliminate size distortion. Once the projection is set, equal area hexagons are created. Each side of the hexagon is 50,000 meters long and the angular difference between each side is 120^o. The area of each hexagon is therefore 2,190 nm^2. This size closely approximates the extent of a 1^o x 1^o hexagon at 10^oN (the practical southern limit of tropical cyclone existence in the Atlantic Basin). Once the hexagons are evaluated, the calculated values are assigned to the central point (centroid) of the polygons. These points represent the area values of the hexagons and are useful for surface interpolation since they are equally spaced apart due to the hexagon's creation in an equal area projection.

A mosaic of 3,375 hexagons covers most of the Atlantic Basin. Figure 3.2 shows the extent of the hexagons. Boundaries were placed on the limits of the hexagons according to the regions that receive plentiful tropical cyclone activity. Areas which see few storms, if any, are not covered by the hexagon tessellation. If an area receives storms very infrequently (such as north of the Cape Verde islands), the sampling size is too small to be meaningful and is therefore not included.

Storm Intensity Change

Calculating the intensity change of a storm is a fairly straightforward endeavor. Each of the storm segments passing through a hexagon are queried for their current intensity and then queried for their intensity at 6 and 24-hours in the future. Since each storm contains four observations per day, the 6-hour intensity change involves capturing the observed intensity for the next record in the HURDAT data set. The 24-hour intensity change involves capturing the observed intensity for the fourth next record in the HURDAT data set. All intensity change calculations use wind speeds measured in knots.

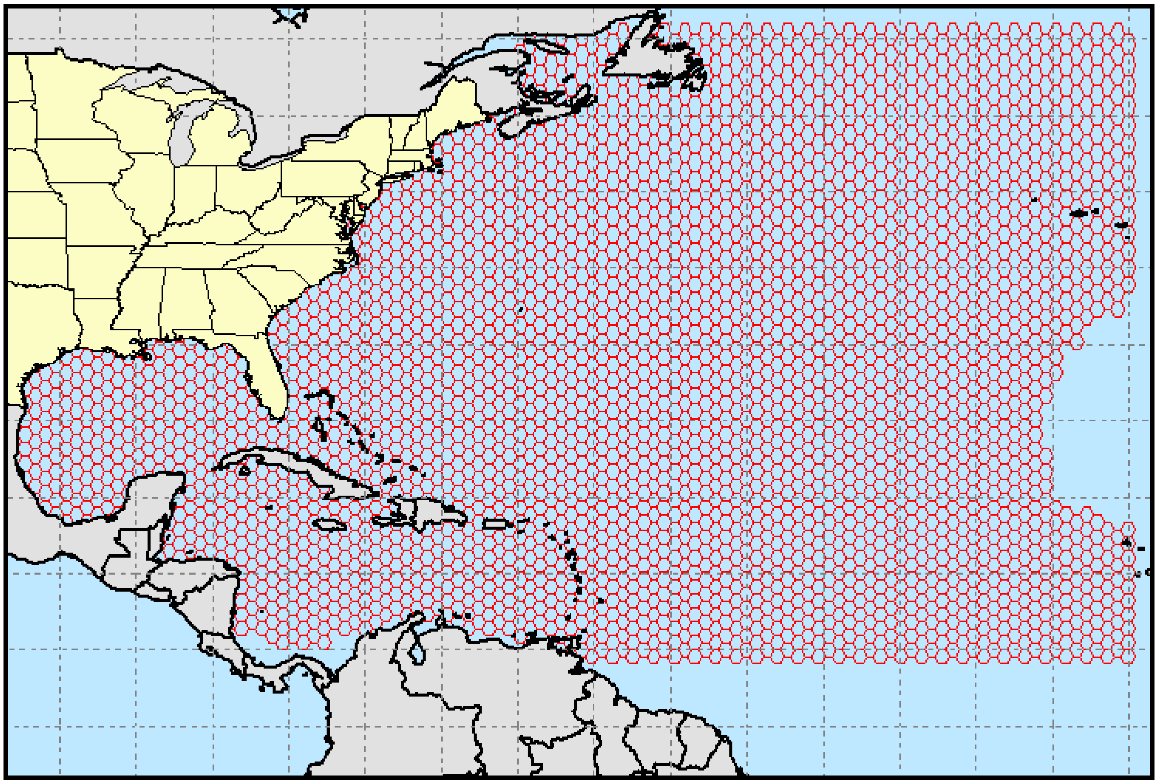

Figure 3.2 Location of 3,375 equal area hexagons used for analysis. Hexagons are omitted north of the Cape Verde Islands due to a lack of historical data. Map is in a Platte Carre projection (raw latitude and longitude coordinates) and therefore the hexagons appear to have different sizes. Each hexagon is exactly 2,190 nm^2 in area.

If a storm passes through a hexagon but no subsequent records exist in the HURDAT data set for that storm, we assume that the storm dissipated. The current minimum threshold for tropical cyclone intensity is 25 knots. Once a storm's winds fall below 25 knots, it is no longer tracked as a tropical cyclone. Over a 6-hour period, if a storm dissipates, a new intensity value of 20 knots is used in the intensity change calculation. Over a 24-hour period, this assumption cannot be made since the storm may dissipate at 6, 12, 18, or 24 hours. If the storm dissipates at 6, 12, or 18 hours, a 24-hour intensity change cannot be calculated. This situation occurs often as a storm makes landfall and weakens rapidly. Therefore, a storm track passing through a hexagon and dissipates 18 hours later is used in the 6-hour intensity change calculation but not in the 24-hour intensity change calculation.

Probability Calculations

Each of the 3,375 hexagons are systematically evaluated against the complete HURDAT data set to determine which storms pass through that shape. No consideration is given to the length of the track through the hexagon. For example, a storm might pass through 15,000 feet of a hexagon while another storm might pass through 150,000 feet of the same hexagon – each storm receives the same weight in all calculations.

When all storms passing through a hexagon are identified, each of those storms are followed to determine their eventual path and to determine if landfall occurred in the contiguous United States. A count is made of all storms that strike the U.S. and all storms that do not strike the U.S. The proportion of points that eventually strike the U.S. is reported as the *a posteriori* probability of eventual landfall. More specifically, the landfall probability is subdivided by state; that is, a probability is computed for eventual landfall in each of the 18 coastal states. Since several states have short coastlines or receive relatively few storms, groups of states and regions are analyzed as well; these groupings are described in the next chapter. As stated earlier, the only other studies looking at where storms come from used larger strike areas of irregular size with no distinction between states (Hope and Neumann 1971; Elsner and Kara 1999).

What actually constitutes a landfall is not easily extracted from the HURDAT data set. The HURDAT file indicates where landfall officially occurred; however, hurricane or tropical storm conditions are not confined to a point. Tropical cyclone conditions are observed over a wide region. For example, Hurricane Rita officially made landfall in southwestern Louisiana in 2005 near the city of Cameron – slightly east of the Texas state line. However, Beaumont, Texas, reported sustained winds of 70 knots (NHC 2006f). If the HURDAT data is interpreted literally, only Louisiana received an impact. Another example from the 2005 tropical season is Hurricane Ophelia. Officially, the hurricane never made landfall but Cape Lookout, North Carolina, reported sustained winds of 65 knots (NHC 2006e). Therefore, an adjustment factor of 30 nautical miles is included to determine if landfall occurred near a state boundary. The typical radius of a tropical cyclone eye is 10-20 nautical miles with an eyewall width of 10 nautical miles (Weatherford and Gray 1988). Therefore, a threshold distance of 30 nautical miles from the coast is used to account for storms passing close enough to unleash the maximum strength of that storm. Using this threshold distance, both Louisiana and Texas are landfall targets of Hurricane Rita and North Carolina is counted as a landfall for Hurricane Ophelia. Because some storms impact multiple states, the combined probability for some of the hexagons is greater than 1.0 (see Figure 3.3).

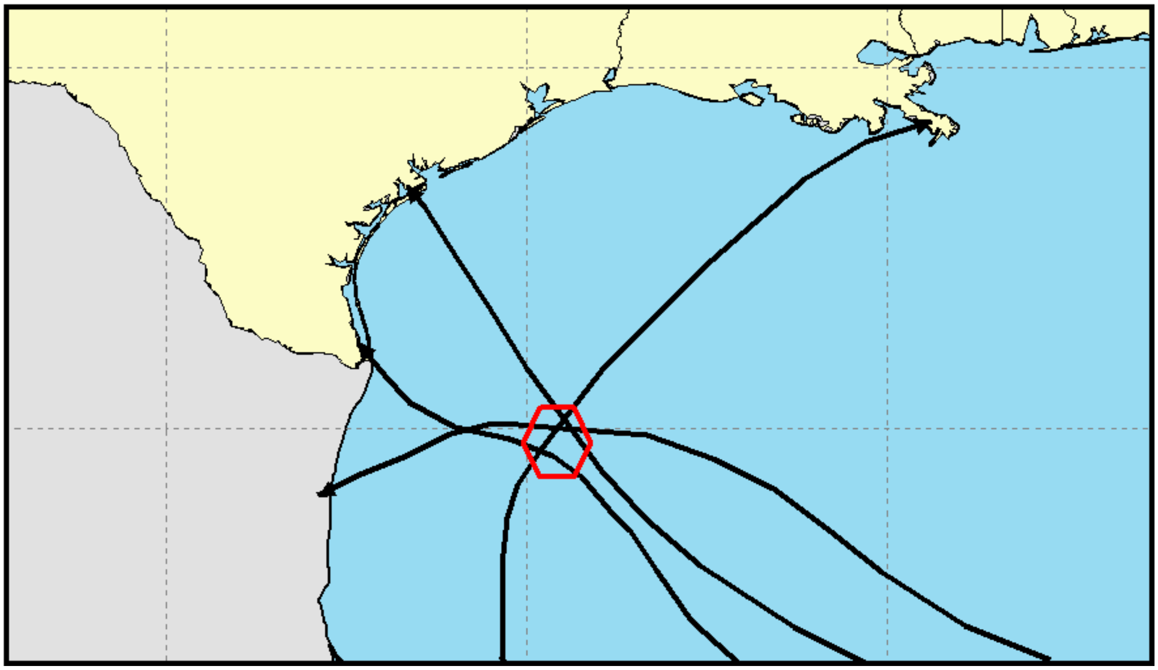

Figure 3.3 Example of hexagon near 25N 94W. In this example, there are a total of four storms, two of which ultimately strike Texas and one that ultimately strikes Louisiana. Therefore, for that region, the probability of a storm eventually striking Texas is 0.5; the probability of striking Louisiana is 0.25. All other coastal states are assigned a probability of 0.0. The probability of a storm passing through that hexagon and eventually striking Mexico is 0.5. The combined probability is 1.25, which is a result of one of the storms striking at the Texas/Mexico border.

A secondary issue involves the storm's previous history. Imagine a hypothetical storm near Nassau in the Bahamas. That storm's prior movement is potentially highly variable. Inspection of previous storm tracks reveals that it is not uncommon for storms in that location to originate from an area near Puerto Rico (northwesterly movement), nor is it uncommon for storms in that location to originate from an area near Havana, Cuba (northeasterly movement). When analyzing the probability of storms passing near Nassau eventually striking the U.S., no assumption is made as to the direction of movement. Therefore, if a storm has already impacted the U.S. mainland and then moves over the Bahamas and out to sea, it is counted as not having any effect on the U.S. for the remainder of its life history.

2005 Major Hurricane Analysis

Several of the major hurricanes of 2005 followed paths which appeared unusual at the time, most notably Hurricane Katrina (NHC 2005). Perhaps the perceived unusualness of the storm's path led residents of New Orleans to not take the storm very seriously. When looking at the tracks of major hurricanes that strike the New Orleans area, Katrina's path doesn't appear quite as unusual. If fact, Hurricane Betsy took a nearly identical path in 1965 (NHC 2005).

Each of the four major storms (100+ knot winds at the time of landfall) that made landfall along the Gulf of Mexico coast in 2005 passed through portions of the Atlantic Basin that may or may not ordinarily contribute hurricanes to the eventual point of landfall. Each of the storms are backtracked to show how they "behaved" in comparison to climatology. Hurricanes Dennis, Katrina, Rita, and Wilma are compared to the expected tracks defined in the historical record. This type of hindcasting is particularly useful for time frames beyond five days – the length of the NHC forecast period.

GIS Analytical Tools

All analytical calculations are performed using the ESRI® ArcGIS™ Geographic Information System (GIS) software package (ESRI 2005) version 9.1. None of the analytical techniques utilize the built-in functionality of the software; however, the Microsoft Corporation® has licensed access to their Visual Basic for Application™ (Microsoft 2001) extensibility to allow supplemental analysis through access of the GIS software's Active X™ controls. Bossak (2003) used a similar programming technique with a previous version of the software to analyze tropical cyclones occurring before the period of record (pre-1851). The software's flexibility enables complex calculations and sophisticated analysis.

CHAPTER 4

RESULTS

Between 1851 and 2004, 522 tropical cyclones struck the United States coastline from Texas to Maine according to the HURDAT data set. In the past, researchers and the general public were left to draw their own conclusions as to where storms typically move by looking at a jumbled set of lines that represent the historical record. Decision makers today need both qualitative and quantitative information so that the public is appropriately prepared for the impacts of these storms.

The landfall probability maps developed from the previously described methodology show ten categories of historical landfall likelihood. The 3,375 hexagons each contain a calculated probability value and are displayed according to the category that the value falls within. Probability values less than 0.02 (2%) are not mapped – these regions are considered non contributors of landfalling storms. The categories are measured as percentages and are as follows: 2-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%, 80-90%, and 90-100%. Each category is mutually exclusive so there is no overlap between consecutive groupings. Values that are exactly at class break boundaries are included in the lower class. The probability values are calculated and displayed for each individual hexagon and therefore are not continuous. If the probability values are assigned to the centroid of the hexagon, a continuous probability surface may be generated; however, the specific surfacing technique chosen will affect the interpolation of values between the hexagon centroids. Therefore, all probability mapping is conducted using the hexagon (polygon) values.

The geographical unit of landfall for this dissertation is an individual state. In the United States, the state political unit maintains much of the responsibility for protection of its citizens and their property. Therefore, each coastal state is evaluated for historical landfall based on the nearly 1,400 storms in the HURDAT data set. Since several of the coastal states have very short coastlines, groupings were made to facilitate analysis. The states and groupings evaluated are as follows: 1) Texas, 2) Louisiana, 3) Mississippi, Alabama, and the Florida panhandle (West of Jefferson County), 4) the Florida peninsula (Jefferson County and all counties east of Jefferson County), 5) Georgia, 6) South Carolina, 7) North Carolina, 8) Virginia, Maryland, and Delaware, 9) New Jersey, 10) New York, 11) Connecticut, Rhode Island, Massachusetts, and New Hampshire, and 12) Maine. In addition, the entire Gulf and Atlantic coastline is evaluated. Table 4.1 lists the number of storms directly striking or passing within 30 nautical miles of each of the 18 coastal states and the grouping listed above.

North Atlantic Basin Landfall Probability

Clearly defined patterns exist in the landfall patterns for the entire Atlantic Basin. Figure 4.1 shows the probability (measured as a percentage) of the entire Atlantic Basin for all 522 storms which eventually made landfall in the Unites States or passed within 30 nautical miles of the coast. As an example of how to read this map, notice the white colored hexagon between Cancun and the western tip of Cuba in Figure 4.1. Thirty-two storms have passed through the area covered by this hexagon between 1851 and 2004. Of those 32 storms, 30 eventually made landfall (or came within 30 nautical miles of

Table 4.1 Count of landfalling storms by state and grouping. The value represents the total number of storms passing within 30 nautical miles of that location for the period 1851-2004. Many storms affect multiple states; therefore, the sum of the individual states exceeds the actual number of United States landfalling storms.

State	Number of Storms
Texas (TX)	117
Louisiana (LA)	121
Mississippi (MS)	93
Alabama (AL)	102
Florida (FL)	245
Georgia (GA)	135
S. Carolina (SC)	108
N. Carolina (NC)	155
Virginia (VA)	89
Maryland (MD)	57
Delaware (DE)	38
New Jersey (NJ)	36
New York (NY)	66
Connecticut (CT)	40
Rhode Island (RI)	37
Massachusetts (MA)	69
New Hampshire (NH)	31
Maine (ME)	49
MS, AL, & FL Panhandle	176
FL Peninsula	196
VA, MD, & DE	92
CT, RI, MA, & NH	73

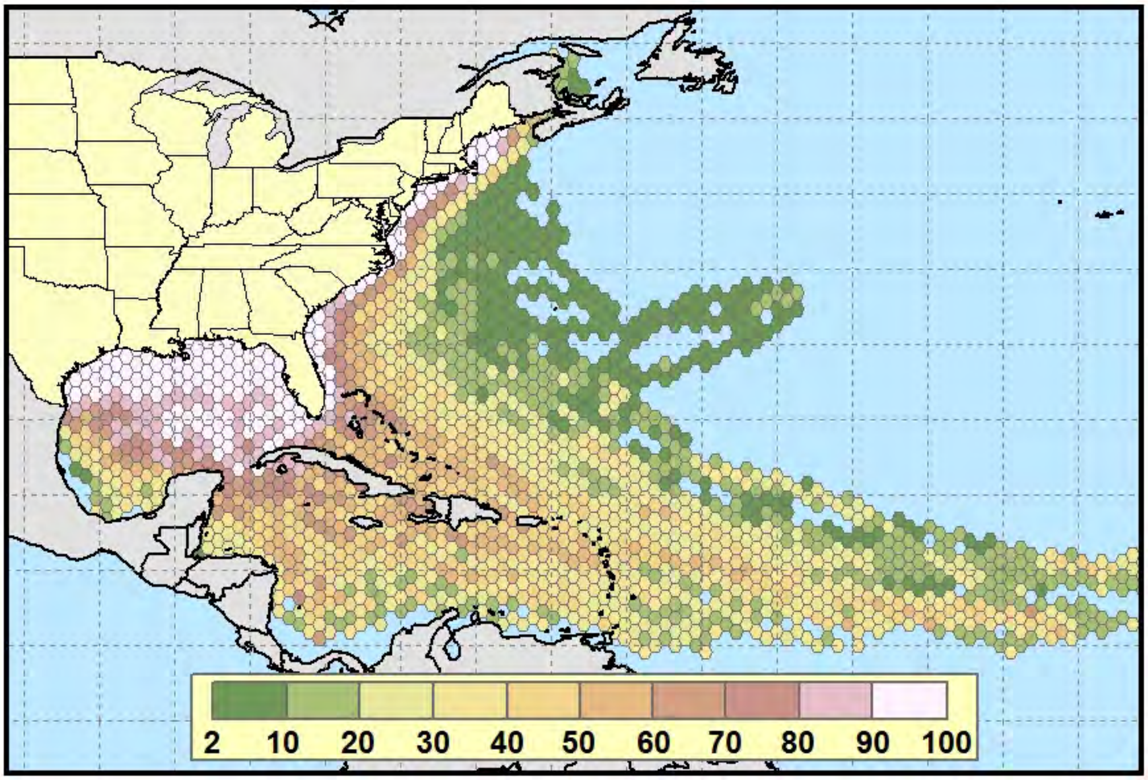

Figure 4.1 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking the United States or coming within 30 nautical miles of the United States (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 522.

landfall) in the United States along the Gulf or Atlantic coasts; therefore, the probability for that hexagon is 0.9375 (30 / 32).

The most notable pattern in Figure 4.1 is the high probability of landfall in the Gulf of Mexico and the immediate East Coast and the diminishing probability moving southeast from those high probability regions. Inspection of Figure 4.2 reveals the average movement of all storms, regardless of eventual landfall, within the HURDAT data set. Storms generally move in predictable directions. In the south-central Atlantic Ocean, tropical cyclones typically move to the west-northwest or northwest. Therefore, the probability of eventual landfall generally follows those arrows.

Several unexpected patterns are shown in Figure 4.1. First, a region of landfall probability exists in the Central Atlantic Ocean east of Bermuda. This is a result of one storm, Hurricane Ginger in 1971, which followed an unusually circuitous path. The hexagons in that region have experienced between 9 and 24 storms throughout the historical period. The one landfalling storm creates probabilities between 0.11 and 0.04 for those hexagons. The second unexpected pattern is the high landfall probability for storms traversing the lowest latitudes evaluated in the Atlantic Basin (the bottom row of hexagons). Similar to the case with Hurricane Ginger, these low latitudes experience relatively few storms. Of those few storms, a large proportion eventually make landfall in the United States. Figure 4.3 shows storm density for the Atlantic Basin for the entire period of record. In essence, this represents the sample size for the probability calculations. Larger hexagons would provide a larger sample size but lessen the spatial resolution.

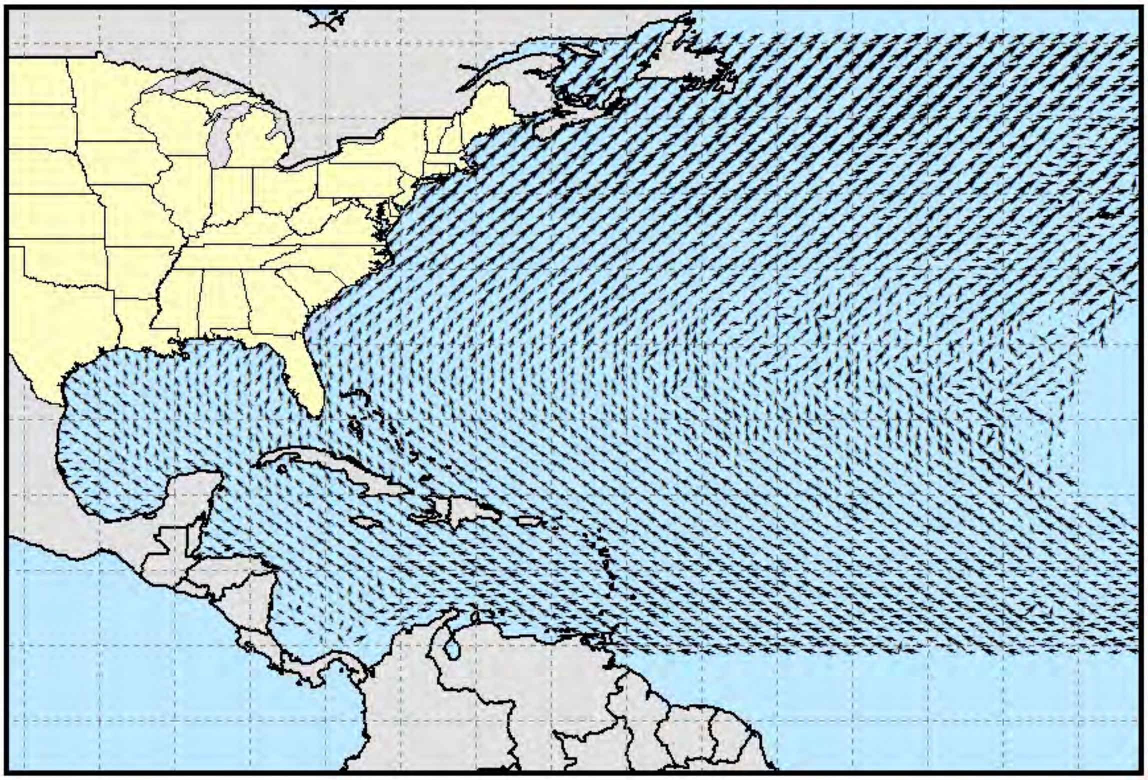

Figure 4.2 Speed and direction of movement (knots) of all storms in the North Atlantic Basin passing through centroid of equal size hexagons. Arrows point toward the direction of movement and the arrow size is proportional to the speed. Period of record is 1851-2004.

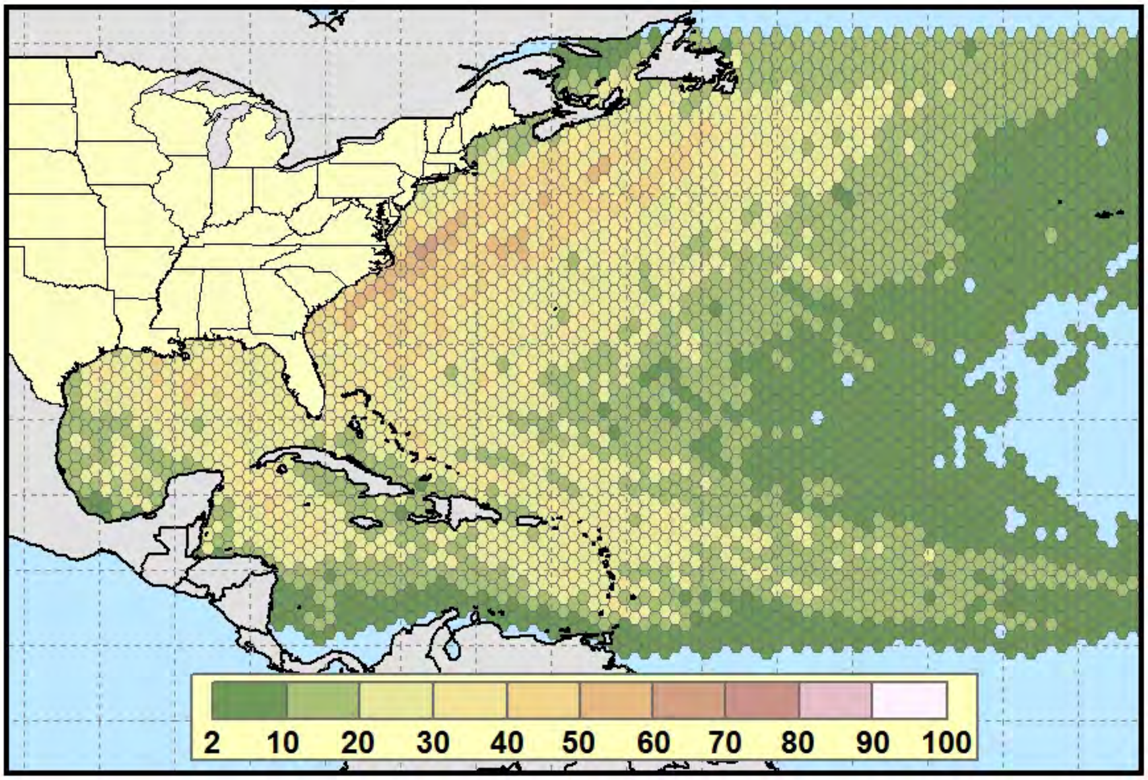

Figure 4.3 Total number of storms passing through equal area hexagons. Period of record is 1851-2004.

The next 12 sections in this chapter will describe the landfall probability maps generated for the 12 states and regions previously described. Appendix B contains a tabular summary of the data displayed in the maps. The states/regions are described in geographical order - southwest to northeast. Probability maps for the states grouped into larger regions or subdivided are shown in Appendix C.

Texas Landfall Probability

Figure 4.4 shows the landfall probability distribution for Texas. Since Texas lies at the western end of the Gulf of Mexico, it is not surprising that Atlantic Basin storms affecting Texas pass through this body of water. The southern Gulf is much more likely to contribute a landfalling storm than the eastern or northern Gulf. Inspection of the average storm movement vectors in Figure 4.2 show that storms in the southern Gulf typically move to the northwest – toward Texas.

Between longitudes 80^{o}W and 60^{o}W (approximately the longitudes of Miami, Florida, and the easternmost Lesser Antilles) storms north of the Greater Antilles generally do not strike Texas. Storms impacting Texas are tightly clustered within a swath of approximately 5^{o} of latitude in this region of the Atlantic Basin. A sharp gradient is apparent in the central Caribbean Sea where storms south of the middle Caribbean do not strike Texas, but north of that line the storms have a high likelihood of ultimately making landfall in Texas.

No storms north of 20^{o}N and east of the Bahamas have ever made landfall in Texas. Only two storms that struck the Florida peninsula from the east later impacted Texas with tropical storm force winds.

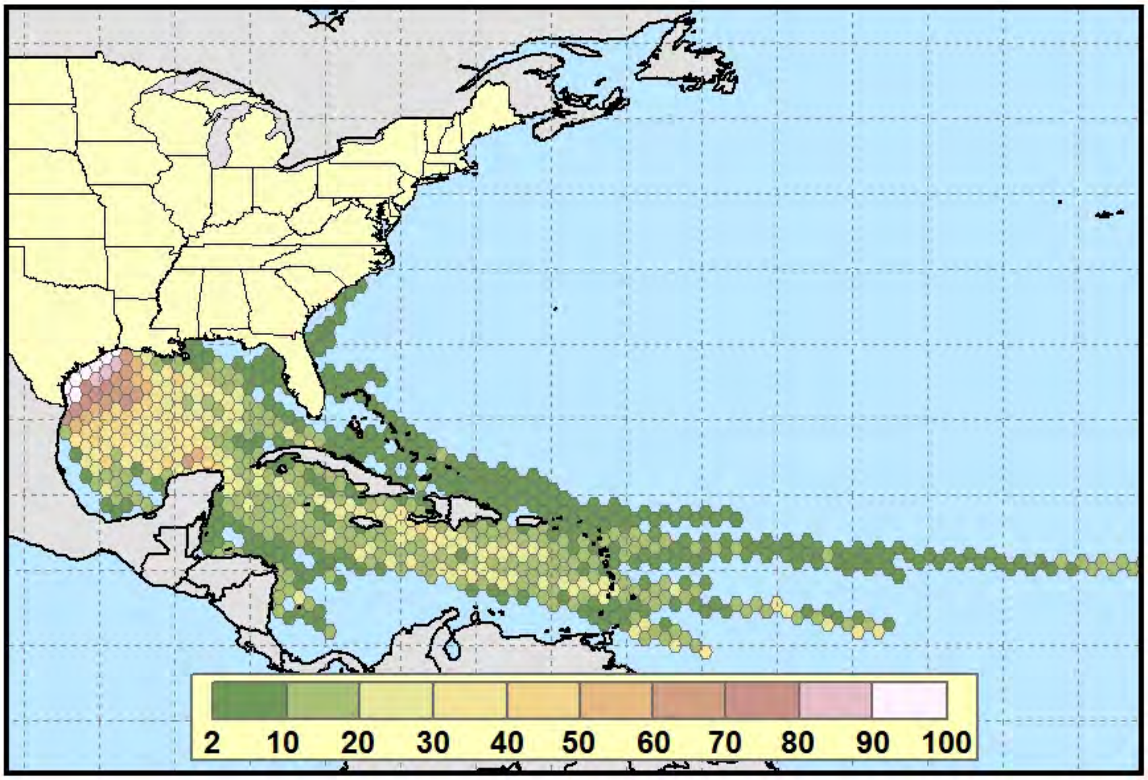

Figure 4.4 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Texas or coming within 30 nautical miles of Texas (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 117.

Louisiana Landfall Probability

Louisiana's landfall probability looks very similar to that of Texas. Figure 4.5 shows the landfall probability distribution for Louisiana. In the Gulf of Mexico, the highest probability hexagons are shifted slightly east of those for Texas; which is not surprising since Louisiana is due east and northeast of Texas. A notable difference is the north/south orientation of the highest probabilities in the Gulf as opposed to the northwest/southeast orientation for Texas. The storm motion vectors in Figure 4.2 show that storms impacting Louisiana frequently arrive from the south.

In the Caribbean Sea, a stretch of high probabilities exists from the western tip of Cuba to Aruba. Storms in the northern Lesser Antilles seldom strike Louisiana and a gap exists immediately north of the Greater Antilles where no storms have ever struck Louisiana from that region. Several storms in the past traversed the Bahamas, crossed Florida, and struck Louisiana. The most recent examples of this are Hurricane Katrina in 2005 (not accounted for in the probability calculations) and Hurricane Andrew in 1992. Very few storms that existed east of 55^{o}W longitude make landfall in Louisiana.

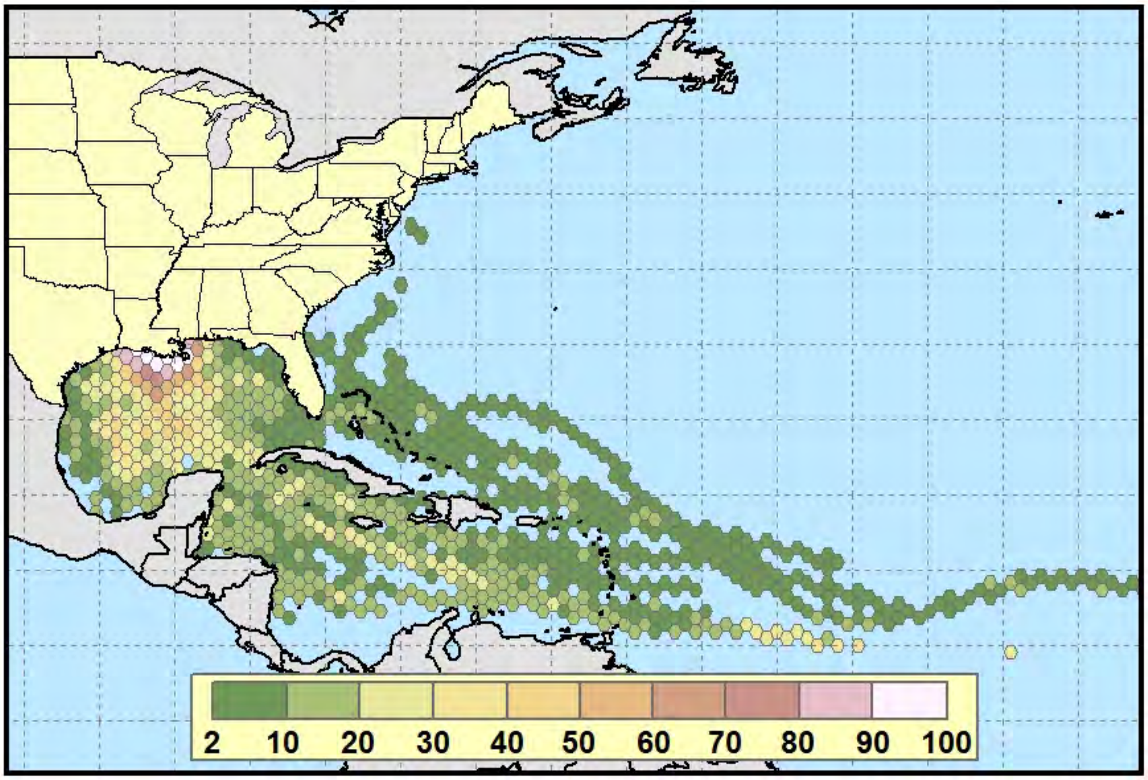

Figure 4.5 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Louisiana or coming within 30 nautical miles of Louisiana (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 121.

Mississippi, Alabama, and Florida Panhandle Landfall Probability

The eastern half of the northern Gulf of Mexico coastline frequently experiences tropical cyclones. Hurricane Opal in 1995, Ivan in 2004, Dennis in 2005, and Katrina also in 2005 all made landfall in this region as major hurricanes (winds > 100 knots). Due to the short distance of coastline for Mississippi and Alabama, these states are grouped with the Florida panhandle to create a homogonous region similar in size to many individual states.

This region experiences tropical cyclones originating from a much larger region than either Texas or Louisiana. In fact, there are 459 hexagons (see Table B.3) whose landfall probabilities (percentage) exceed 20% for this region (Figure 4.6 shows the landfall probability distribution for this region). This exceeds the combined value for Texas and Louisiana. The Greater Antilles no longer appear as a natural barrier to storm movement. Many storms appear to pass north of Cuba, cross the Florida peninsula, and strike this region. Once the latitude of Cape Canaveral is achieved along the East Coast of Florida, the probability of future landfall in the northern Gulf coast drops dramatically.

Individual probability maps for Mississippi, Alabama, and Florida are located in Appendix C. A map showing the boundary between the Florida peninsula and the Florida Panhandle is shown in Appendix D.

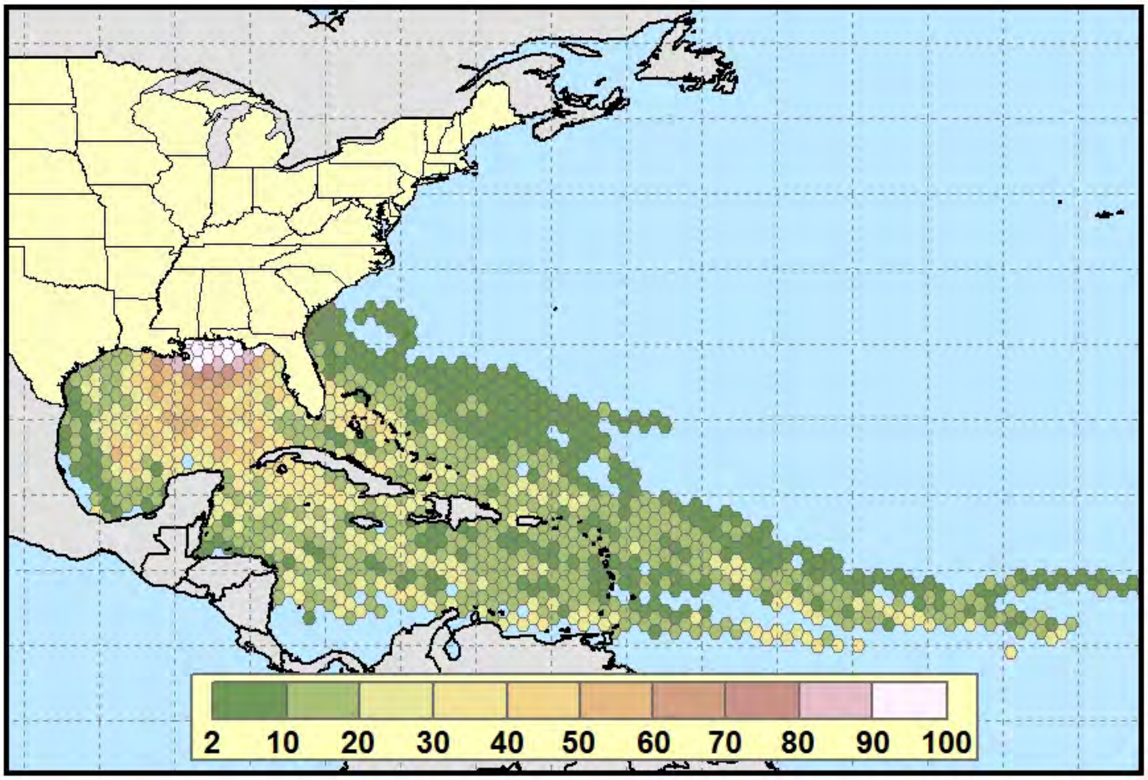

Figure 4.6 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Mississippi, Alabama, or the Florida panhandle or coming within 30 nautical miles of Mississippi, Alabama, or the Florida panhandle (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 176.

Florida Peninsula Landfall Probability

The Florida peninsula region is mutually exclusive from the panhandle portion of Florida used in the previous region. Figure 4.7 shows the landfall probability distribution for the Florida peninsula. Unlike the previous regions and states, the Florida peninsula receives tropical cyclones from three different directions – east, south, and west. The landfall probability for the area west of the Florida peninsula in the Gulf of Mexico decays at a slower rate than the area in the open Atlantic to the east. The southwest Caribbean contributes a much larger proportion of storms to the Florida peninsula than Texas, Louisiana, or the eastern portion of the northern Gulf coast.

Many storms that existed east of 55^{o}W longitude at some point eventually made landfall in the Florida peninsula. Therefore, the "Cape Verde" storms that originate in the extreme eastern Atlantic are more likely to strike peninsular Florida. In the Lesser Antilles, the northern islands are more likely to experience storms that make a future landfall in the Florida peninsula; this is markedly different from the probabilities for Texas and Louisiana.

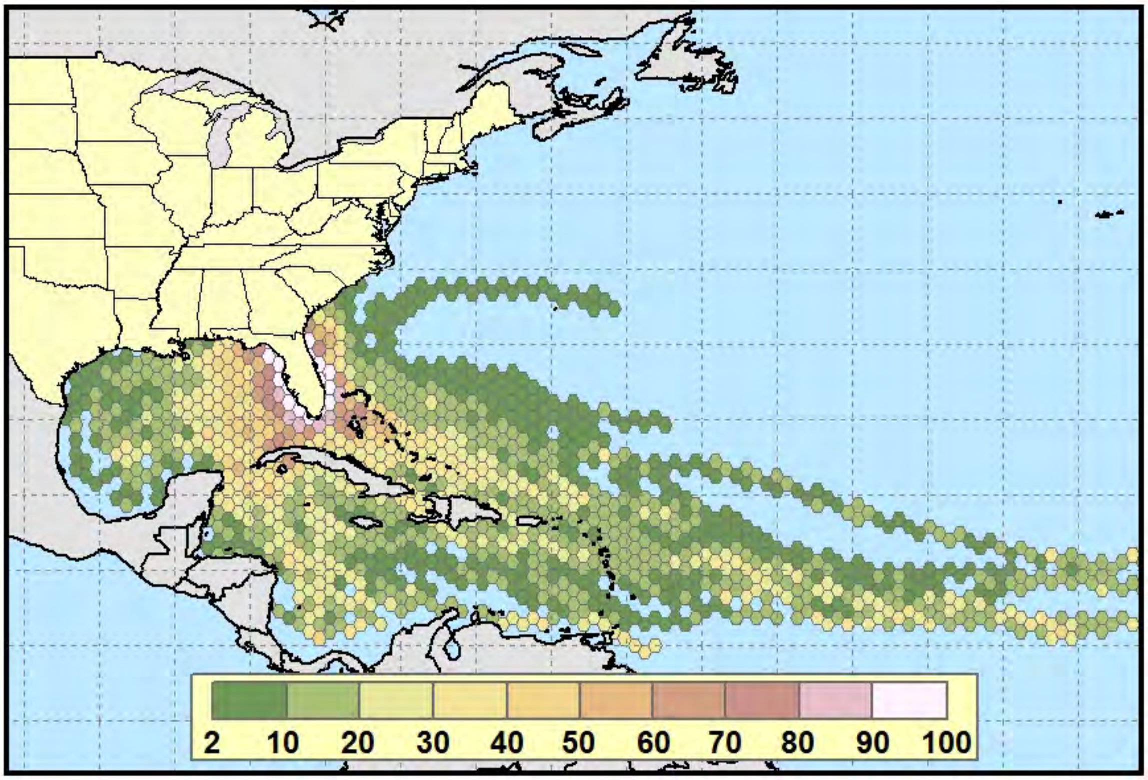

Figure 4.7 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking the Florida peninsula or coming within 30 nautical miles of the Florida peninsula (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 196.

Georgia Landfall Probability

The state of Georgia is unique in that it receives active tropical cyclones from the open Atlantic (east) and from the Florida panhandle (south). Even though the storms moving from the south are likely weaker than the ones striking the Georgia coastline, damaging winds are possible in either scenario – a 40 knot wind is the same if it originated from the south or the east. For this reason, Georgia experiences more tropical cyclones than either Texas or Louisiana despite a relatively short coastline. Figure 4.8 shows the landfall probability distribution for the state of Georgia.

There is no single region of the Atlantic Basin that contributes more storms to Georgia than any other region. There are only 123 hexagons whose Georgia landfall probability exceeds 20% (See Table B.5). This is a much smaller number than Texas or Louisiana. The storms that impact Georgia do not travel as far as those that strike the Gulf coast or Florida's East Coast. The probability values east of 55^{o}W longitude and south of 20^{o}N latitude are much smaller than the aforementioned states and regions.

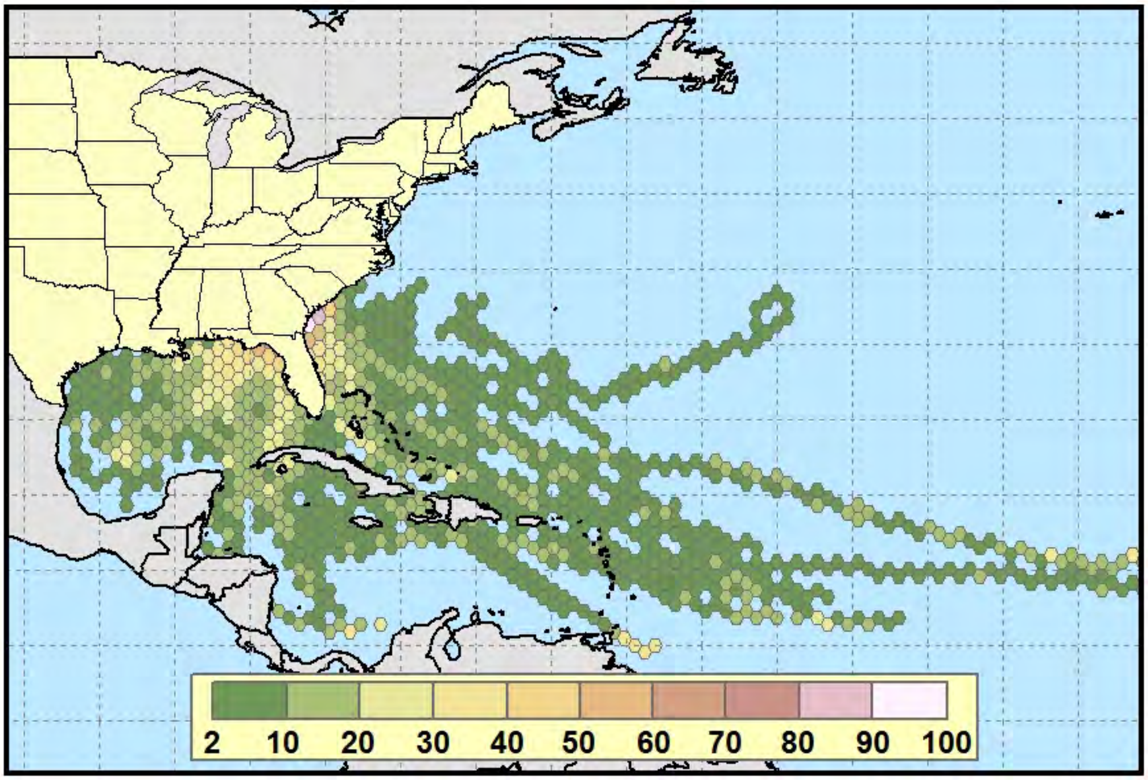

Figure 4.8 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Georgia or coming within 30 nautical miles of Georgia (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 135.

South Carolina Landfall Probability

South Carolina experiences some storms crossing the Florida panhandle and passing through southern Georgia that retain tropical storm force winds (35+ knots); this represents a minor contribution to the total number of storms. The two primary scenarios for South Carolina's landfalling storms are: A) the storm crosses the Florida peninsula and travels in a north-northeasterly direction and strikes the coast from the south, and B) the storm strikes from the open Atlantic traveling in a northwesterly direction. Figure 4.9 shows the landfall probability distribution for South Carolina.

The landfall probability values are comparatively small for hexagons in the Caribbean Sea, and the western Gulf of Mexico. Storms crossing the Florida peninsula tend to originate in the eastern Gulf and cross Florida north of Tampa. A surprising number of hexagons in the extreme eastern Atlantic Ocean (especially between 12^{o}N and 14^{o}N latitude) contain high landfall probabilities for South Carolina. Unlike many states and/or regions, there is not a steady increase in probability values as the distance to the coast decreases. This spatial variability indicates that storms in close proximity to South Carolina move in a variety of directions.

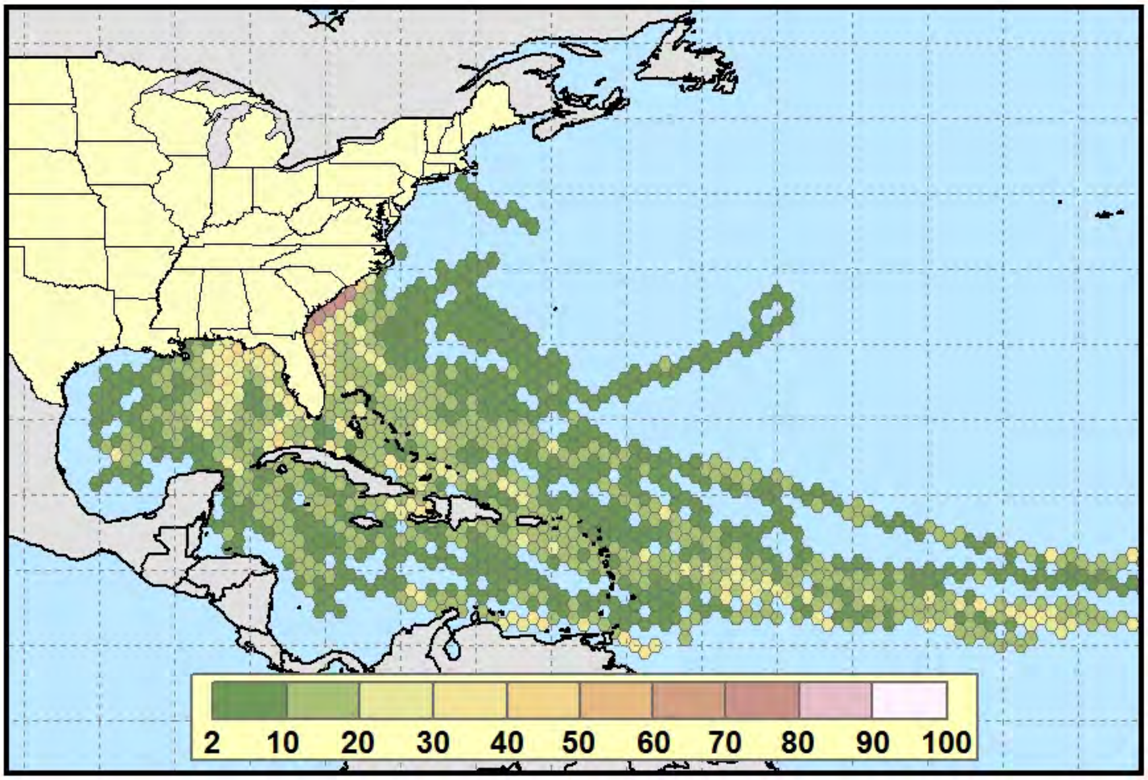

Figure 4.9 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking South Carolina or coming within 30 nautical miles of South Carolina (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 108.

North Carolina Landfall Probability

The portion of the Atlantic Basin immediately east of the North Carolina outer banks experiences more tropical cyclones than any other portion of the Basin (see Figure 4.3). This region marks the intersection of storms recurving around the subtropical high pressure cell (Tannehill 1945) and storms crossing Florida from the Gulf of Mexico.

The storms impacting the State of North Carolina (Figure 4.10 shows the landfall probability distribution for North Carolina) are almost exclusively moving in a northward direction – the landfall probability declines dramatically for hexagons located due east of the State. The average storm vectors shown in Figure 4.2 indicate that storms usually move northeast in the vicinity of North Carolina.

The far eastern Atlantic contributes a sizeable proportion of storms ultimately making landfall in North Carolina. A corridor of high probability hexagons exists from the Cape Verde islands to north of Puerto Rico and east of the Bahamas. A secondary high probability corridor is in the northeastern Gulf of Mexico and the Florida peninsula between Tampa and Jacksonville.

The 2-10% probability hexagons southeast of New England represent a single storm which formed in the region and moved southeast, south, southwest, and eventually west before making landfall in South Carolina.

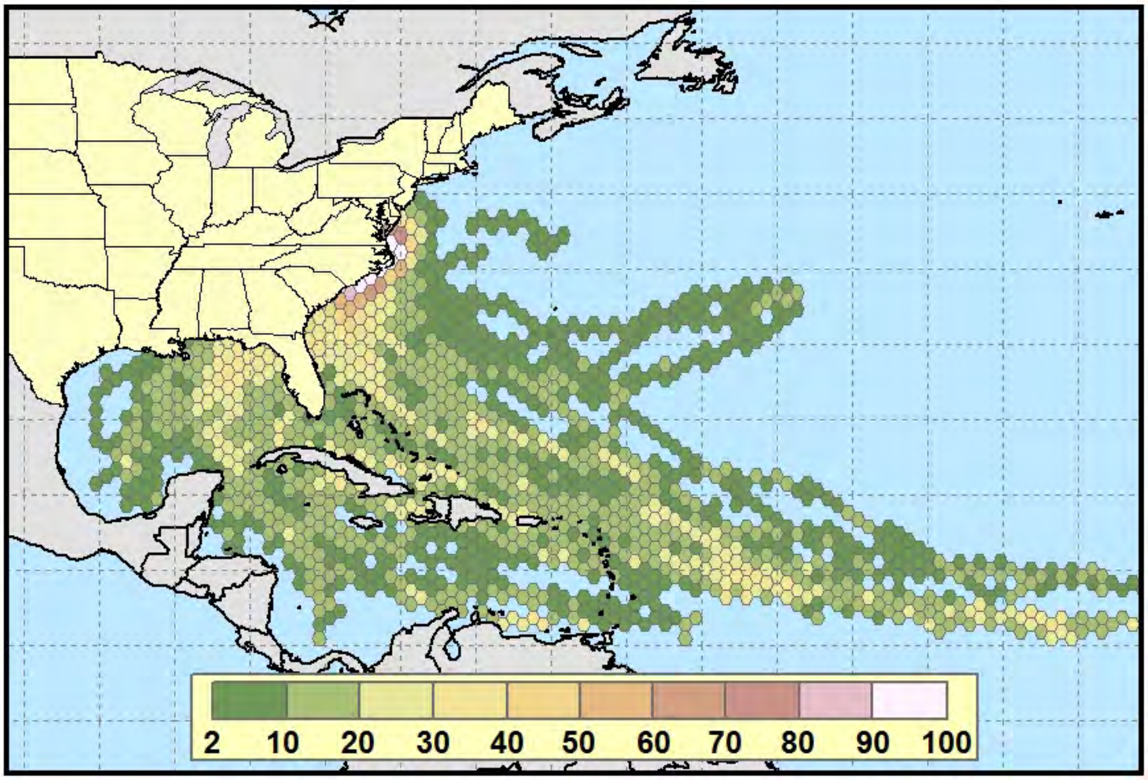

Figure 4.10 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking North Carolina or coming within 30 nautical miles of North Carolina (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 155.

Virginia, Maryland, and Delaware Landfall Probability

These states are combined due to their short, irregular coastlines and the similarity in spatial patterns of landfalling storms. In addition, the number of landfalling storms in this region is smaller than surrounding areas in large part because of the orientation of the coastline. Nearly every storm impacting Virginia eventually impacts Maryland and Delaware (see Table 4.1). Figure 4.11 shows the landfall probability distribution for the combined coastline of Virginia, Maryland, and Delaware.

A very noticeable pattern is evident in the probability pattern for this region. Most landfalling storms originate at low latitudes east of the Lesser Antilles and travel west-northwest. Once they cross the latitude of Puerto Rico, the storms move northwest and cross near or over North Carolina before entering the region. A majority of the storms impacting this region did not directly strike the coast from the open ocean; instead traveling across a portion of eastern North Carolina.

The extreme northeastern Gulf of Mexico contains several hexagons with probabilities greater than 20%. Similar to North Carolina, a number of storms crossing the Florida peninsula from the Gulf turn northward and hug the East coast, ultimately impacting this region.

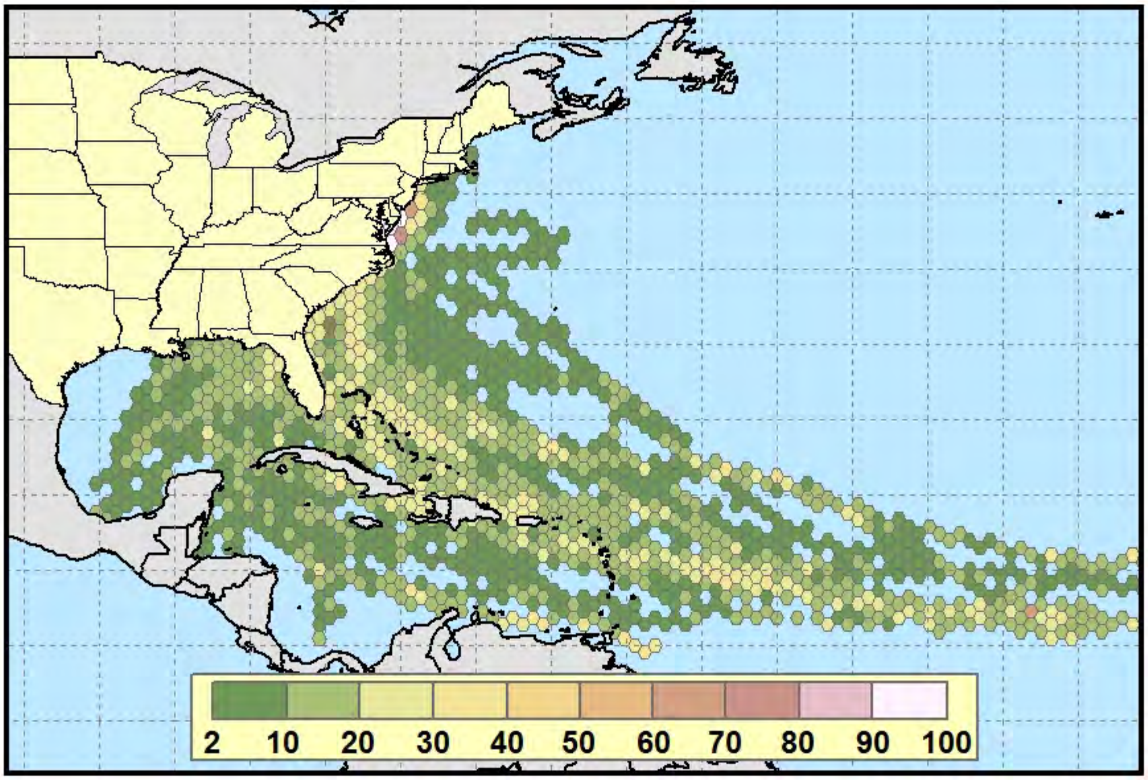

Figure 4.11 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Virginia, Maryland, or Delaware or coming within 30 nautical miles of Virginia, Maryland, or Delaware (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 192.

New Jersey Landfall Probability

Only 19 hexagons in the Atlantic Basin contain a greater than 50% probability of eventually striking New Jersey - most of those intersect the New Jersey coastline or are inland. The southern half of New Jersey's coastline is oriented southwest to northeast which captures storms moving from the south. Figure 4.12 shows the landfall probability distribution for New Jersey.

A large proportion of New Jersey's storms pass through the Atlantic Basin north of Puerto Rico and travel in a northwesterly direction to an area east of the Bahamas. Once the storms reach 75^{o}W longitude, they typically turn due north if they impact New Jersey. Many of these storms also made landfall in the Outer Banks of North Carolina. Storms that are south of the Greater Antilles or in the Gulf of Mexico rarely affect New Jersey. However, this analysis only evaluates storm with winds greater than 35 knots. If storms at tropical depression strength are included (not shown), the Gulf of Mexico hexagons contain much higher probability values.

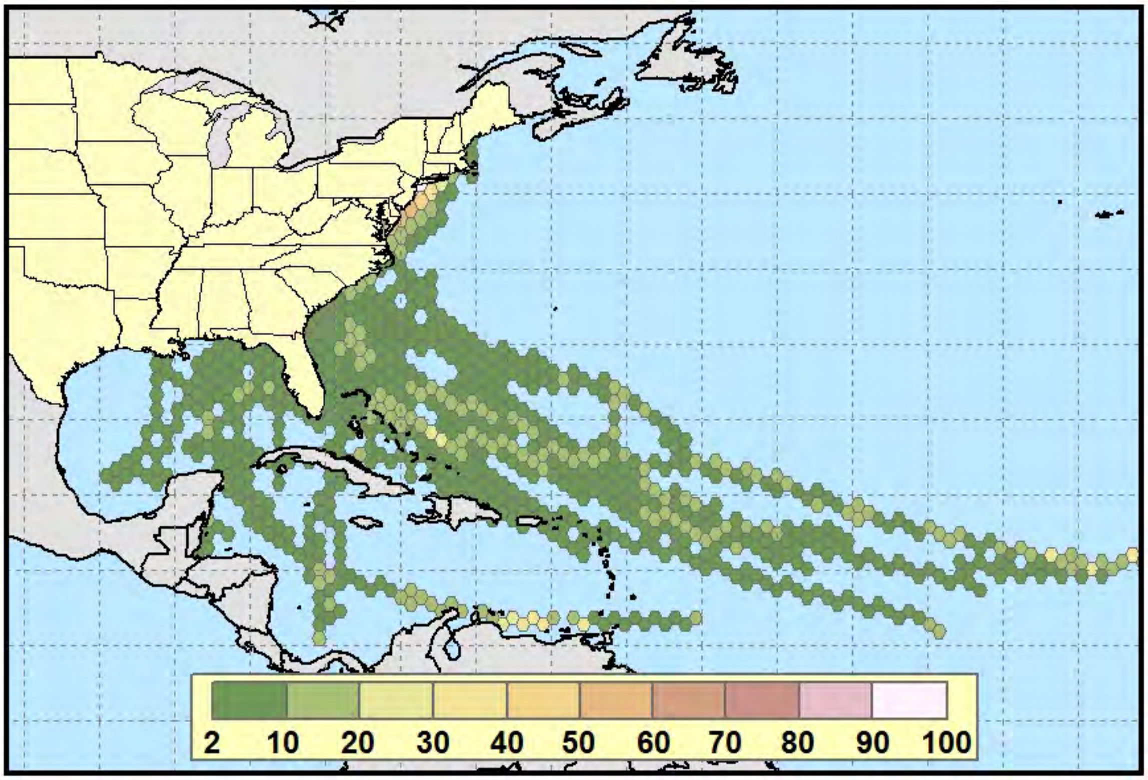

Figure 4.12 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking New Jersey or coming within 30 nautical miles of New Jersey (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 36.

New York Landfall Probability

The reason New York is included as a distinct region is the shape and orientation of Long Island. This section of the state is oriented perpendicular to the track of storms impacting this region. Figure 4.13 shows the landfall probability distribution for New York. The map of landfall probabilities is similar to that of New Jersey but with several important differences. First, due to the geographic shape of the state, more storms have impacted New York state than New Jersey. Second, since New York extends farther east in longitude, more storms recurving around the subtropical high pressure cell intersect the eastern portion of Long Island. This is seen by inspecting the landfall probability hexagons in the vicinity of the North Carolina Outer Banks; the probabilities are substantially higher than for New Jersey.

A tight corridor (5^o to 10^o of latitude) of relatively high probability hexagons are present from the eastern Atlantic Ocean to the area east of the Bahamas. From there, storms impacting New York state parallel the eastern seaboard and strike from the south or south-southwest. Only a few storms crossed the Florida peninsula from the Gulf of Mexico and moved up the East Coast.

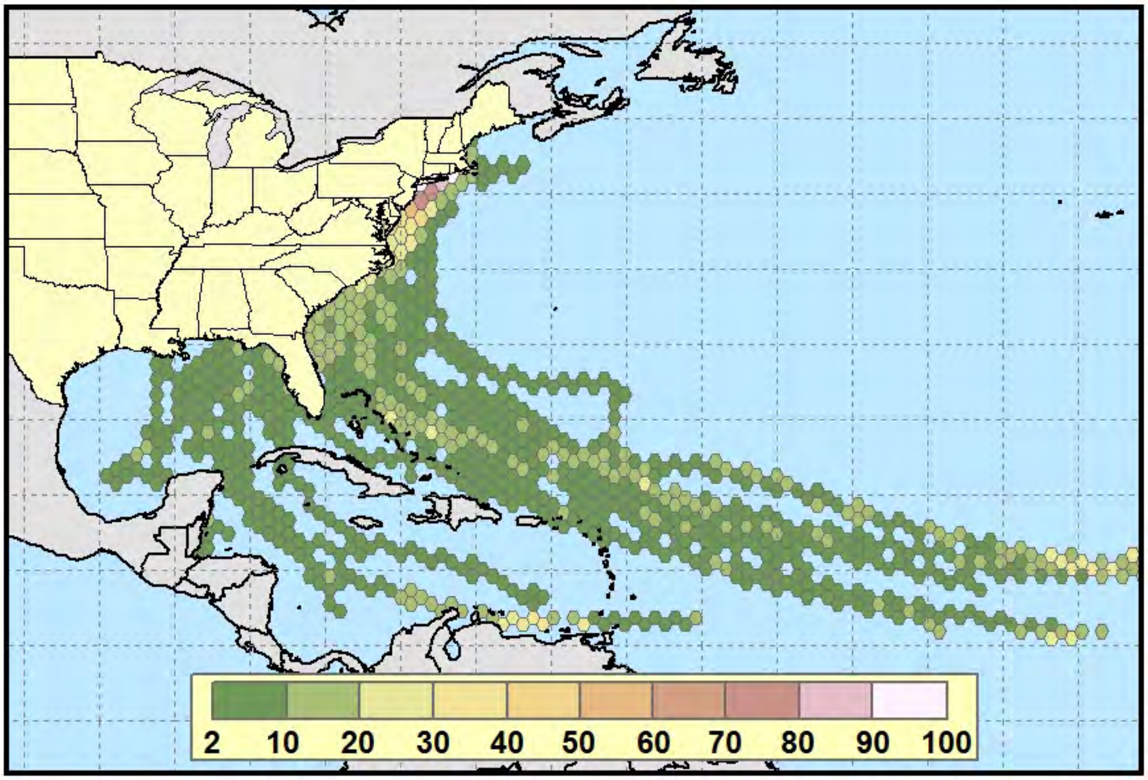

Figure 4.13 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking New York or coming within 30 nautical miles of New York (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 66.

Connecticut, Rhode Island, Massachusetts, and New Hampshire Landfall Probability

The storms impacting these four states are highly correlated; i.e., a storm impacting one of the states most likely impacted the other three states, with one exception. A number of storms pass within 30 nautical miles of Cape Cod, Massachusetts, without affecting the other states. The eastern extent of Cape Cod allows storms that recurve father east to still strike this region. This also enables storms crossing over Florida from the Gulf of Mexico to strike this region. Figure 4.14 shows the landfall probability distribution for this region.

The vast majority of storms striking Connecticut, Rhode Island, Massachusetts, and New Hampshire travel across the open Atlantic northeast of the Greater Antilles. This pattern of storm movement is similar to all states and regions north of North Carolina. Storms in the vicinity of the Cape Verde islands near 15^{o}N occasionally make landfall in this region. The lower latitude "Cape Verde" storms generally continue in a westward direction and do not make landfall in southern New England.

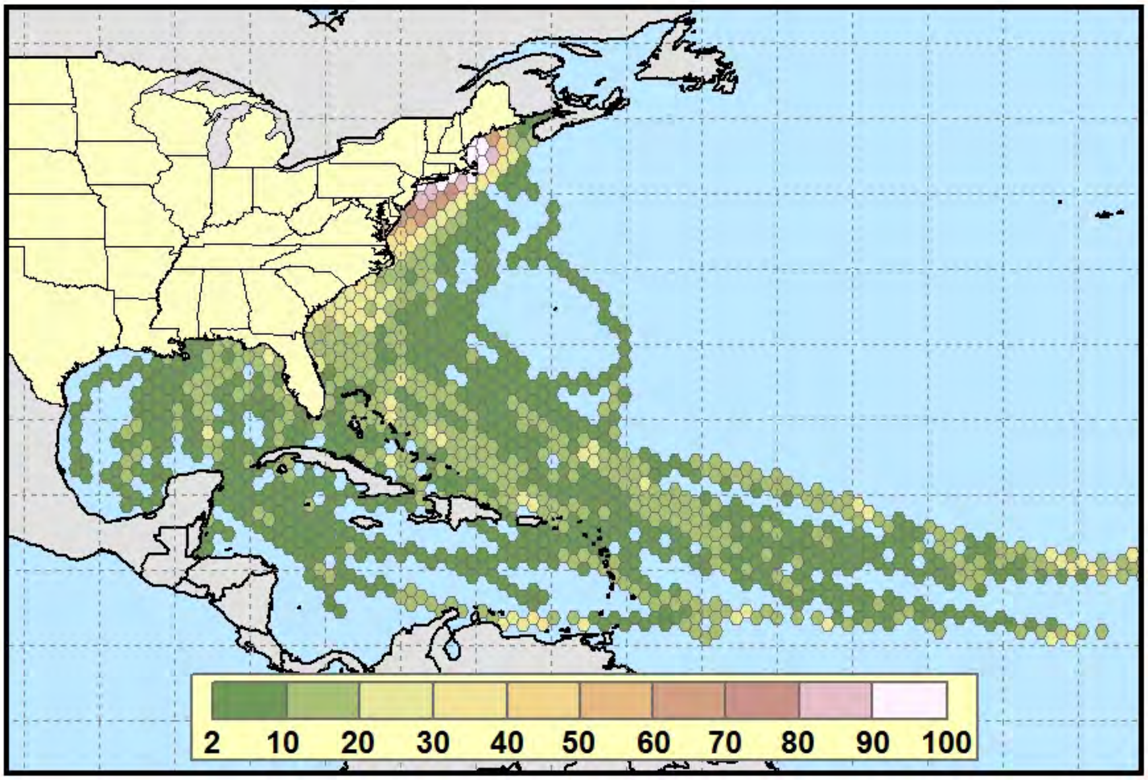

Figure 4.14 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Connecticut, Rhode Island, Massachusetts, or New Hampshire or coming within 30 nautical miles of Connecticut, Rhode Island, Massachusetts, or New Hampshire (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 73.

Maine Landfall Probability

Maine lies north of the latitude where storms recurve around the subtropical high pressure cell. Consequently, few storms strike this region; the ones that do strike Maine take one of two paths. First, a number of the storms strike or pass just east of the easternmost portion of the state. Second, many storms cross over southern New England and enter Maine from the south still at tropical storm or even hurricane strength. Figure 4.15 shows the landfall probability distribution for Maine.

There is no region of the Atlantic with an especially high probability for contributing storms to Maine. The portion of the Atlantic Basin with the highest probabilities is similar to the other states north of North Carolina; i.e., northeast of the Greater Antilles and along the East Coast of the United States. Storms entering the Caribbean Sea infrequently affect Maine and only a few storm in the Gulf of Mexico eventually make landfall in Maine.

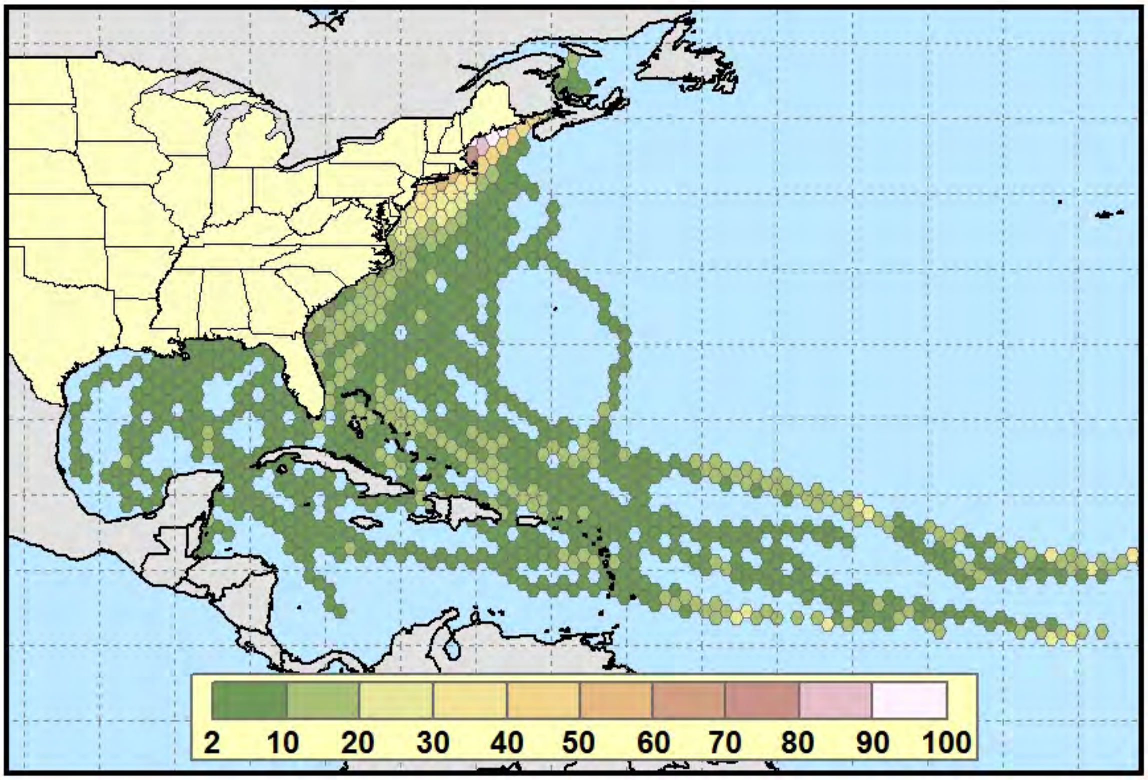

Figure 4.15 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Maine or coming within 30 nautical miles of Maine (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 49.

Summary of Landfall Probability

The different regions of the Atlantic Basin contribute storms to different portions of the United States coastline. Figure 4.16 shows the 3,375 hexagons covering the Atlantic Basin and the state containing the highest likelihood for landfall from that hexagon. Table 4.2 contains a tabular version of Figure 4.16. If more than one state contains the highest likelihood for eventual landfall, no distinction is made to account for the number of states; each is assigned the category "multiple." For example, some hexagons contain equal landfall probabilities for five states (total of 35 hexagons) and other hexagons contain equal probabilities for only two states (total of 238 hexagons).

Many areas on the map that show the highest landfalling probabilities are close in proximity to the state of measurement. One would expect hexagons adjacent to Louisiana (or some other state) to show that Louisiana had the highest landfall probability for that hexagon. As distance increases from the United States, the likelihood of a hexagon's maximum state probability indicating "multiple" increases. This is due to two reasons. First, a smaller sample size means that fewer combinations of probabilities are possible. Second, storms in the eastern Atlantic (far from land) are more likely to recurve around the subtropical high pressure cell and impact multiple states. A storm that strikes Virginia is likely to impact North Carolina, Maryland, Delaware, New Jersey, and possibly other states.

States and regions with a large geographical extent and a large number or landfalling storms (Texas, Louisiana, Florida, and North Carolina) represent the majority of the area in the Atlantic Basin in Figure 4.16. The region of the Atlantic Basin that contains storms most likely to strike Florida is larger than for any other state. Since

Florida receives storms from three directions, the size of maximum probability is not surprising. Interestingly, storms in the central Caribbean Sea are more likely to strike Texas or Louisiana than Florida. North Carolina is similar to Florida with a large number of storms in the Atlantic Basin more likely to strike North Carolina compared to other states or regions. The regions on Figure 4.16 that show the highest probability for North Carolina are immediately north and northeast of the regions showing where Florida is the most likely state for landfall.

East of 70^{o}W and north of 25^{o}N, no discernable pattern exists to show which state has the highest historical likelihood of landfall; except that none of the states are along the Gulf of Mexico coastline. In addition, many states show the highest landfall probability not near their coast but in the Central Atlantic.

In the Gulf of Mexico, the states with the highest landfall probability are stratified in a north south direction. This is likely an artifact of the shape of the coastline - Texas oriented southwest to northeast, Louisiana oriented east-west, and Florida oriented several directions.

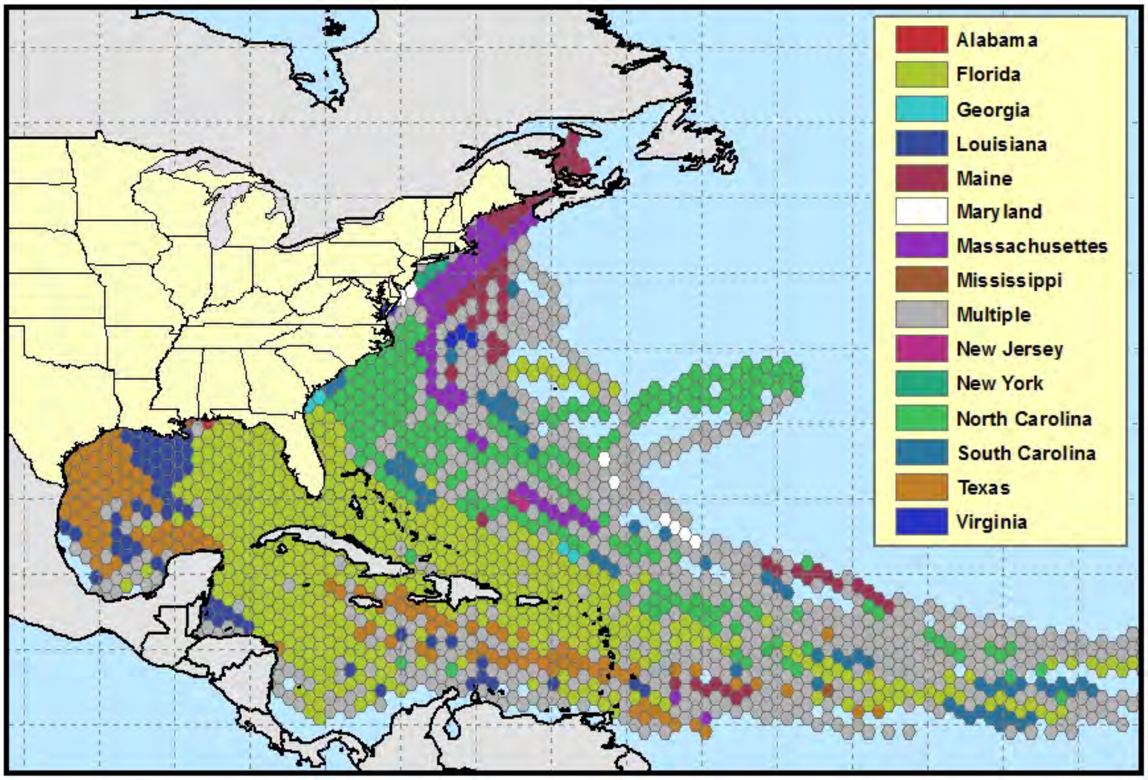

Figure 4.16 The state whose landfall probability is highest for the North Atlantic Basin for all storms passing through equal area hexagons. Period of record is 1851-2004.

Table 4.2 Count of hexagons with the highest landfall probability for each state along the Atlantic and Gulf of Mexico coastline. This represents a tabular version of the map in Figure 4.16.

State	Number of Hexagons
Texas (TX)	145
Louisiana (LA)	83
Mississippi (MS)	3
Alabama (AL)	3
Florida (FL)	528
Georgia (GA)	6
S. Carolina (SC)	66
N. Carolina (NC)	211
Virginia (VA)	9
Maryland (MD)	15
Delaware (DE)	0
New Jersey (NJ)	5
New York (NY)	3
Connecticut (CT)	2
Rhode Island (RI)	0
Massachusetts (MA)	45
New Hampshire (NH)	0
Maine (ME)	72
Multiple	625
None	1554

Days Until Landfall

The National Hurricane Center publishes forecasts on active tropical cyclones for 120-hours in the future (NHC 2006c). Assuming the forecast is accurate, only storms in a portion of the Atlantic Basin are within landfalling range. The rest of the Atlantic Basin is beyond the limit of current forecast ability. The following quote from the NHC in the forecast discussion (#23) for Hurricane Isabel illustrates the problem with long range tropical cyclone forecasts.

> The big question continues to be what will happen beyond the 5-day forecast period. It is still impossible to state with any confidence whether a specific area along the U.S. coast will be impacted by Isabel. This will likely depend on the relative strength and positioning of a mid-troposphere ridge near the East Coast and a mid-latitude trough to the west or northwest around the middle of next week. Unfortunately, we have little skill in predicting the evolution of steering features at these long ranges (NHC 2003).

This forecast discussion was issued 6.75 days prior to landfall on the North Carolina coast when Hurricane Isabel was still a Category 5 storm. Beyond five days, initialization problems and model resolution prohibit meaningful forecasts. At some point in the future, numerical forecasts are superceded by climatology. Figure 4.17 shows the length of time that all storms eventually making landfall in the United States needed to reach the coast.

If a storm is within the “<5” category in Figure 4.17, forecasts from the NHC might indicate a potential landfall somewhere along the coast assuming the storm is moving at a minimum speed threshold and is moving in the direction of the U.S. Climatology is important in this region for a variety of reasons. First, when the atmospheric dynamics are complicated or not well established, climatology provides a guide for future movement. Second, statistical and numerical computer models are programmed to not stray too far from climatology.

In the regions labeled “5 – 10” and “>10” days away from the U.S., landfall climatology is the best guide to future strike potential. On Figure 4.17, storms south and east of a line from Belize City, to east of Jamaica, to Hispaniola, to Puerto Rico, to east of Bermuda, are historically more than five days away from landfall in the U.S. No distinction is made for the portion of the coast affected. For example, storms near Puerto Rico that make landfall in the contiguous U.S. generally strike between Florida and North Carolina. The calculated length of time until landfall follows where the storms historically move. If the storm near Puerto Rico bypassed the Atlantic coast and hit Texas instead, the length of time would be several days more. Maps showing time until landfall by state or region would look somewhat different than Figure 4.17.

Storms in the southern Caribbean Sea and east of the Lesser Antilles’ longitude take an average of 5 or more days to impact the United States; if at all. The combined knowledge of historical landfall probability and length until potential landfall enables the public to make decisions regarding hurricane preparations.

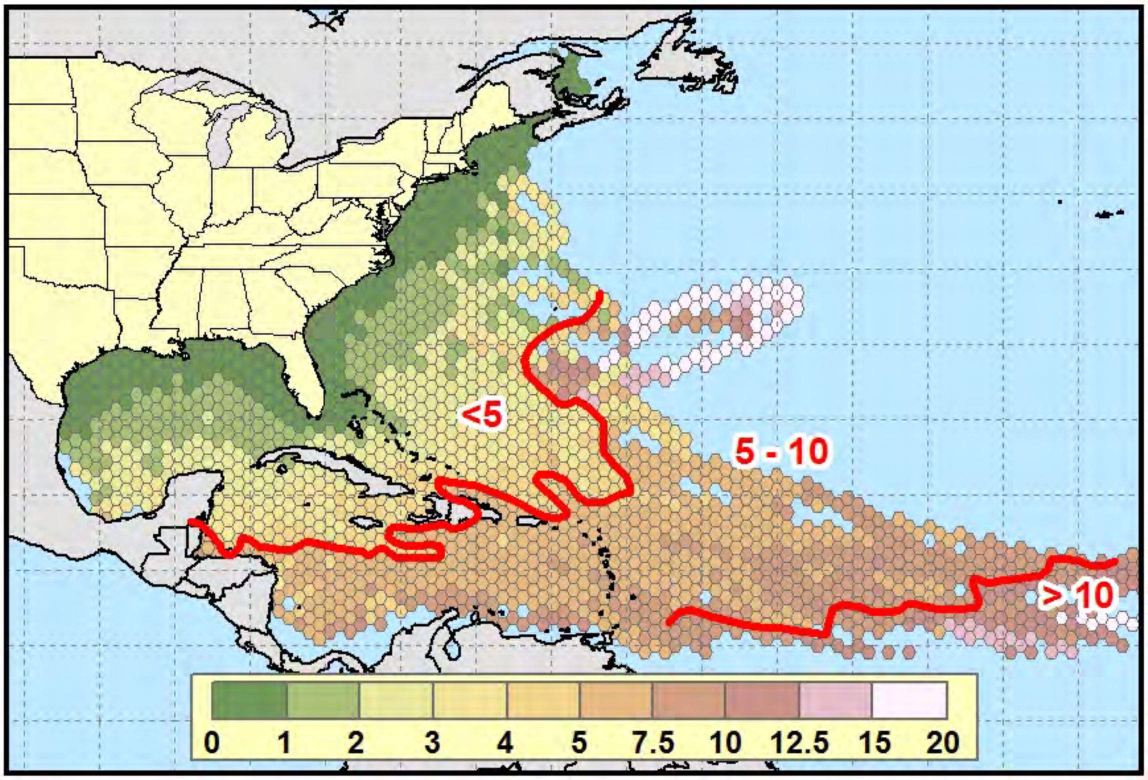

Figure 4.17 Length of time (days) until landfall of all storms in the North Atlantic Basin passing through equal area hexagons that eventually made landfall. Period of record is 1851-2004.

Intensity Change Analysis

Many factors contribute to the change in intensity of tropical cyclones in the Atlantic Basin. Over 150 years of data allow calculations of intensity change to identify regions of strengthening and weakening. Just as with the landfall probability calculations, each of the 3,375 hexagons were systematically analyzed and every storm passing through a hexagon has its initial intensity (wind speed measured in knots) recorded and the intensity six and twenty-four hours later recorded. Figures 4.18 and 4.19 show the 6-hour and 24-hour intensity change respectively.

Much of the Atlantic Basin south of 25^{o}N and open areas of the Caribbean Sea and Gulf of Mexico are conducive to strengthening. Certain corridors (northwest of the Greater Antilles, southern half of the Gulf of Mexico) are highly conducive to strengthening. Not surprisingly, the areas of storm intensification broadly follow the storm tracks in Figure 2.1 south of the subtropical high pressure cell.

The areas near the U.S. coastline show dramatic storm intensity decreases. The region around the Greater Antilles shows a similar pattern but to a lesser degree. The pattern is most evident in the 24-hour assessment. Part of this is the effect of landfall and storm dissipation. If a storm is 150 nautical miles due south of the Louisiana coast and moving north at ten knots, in 24 hours the storm will be inland for a period of nine hours. If the initial intensity is a wind speed of 100 knots, 24 hours later the storm might have winds of only 40 knots. The weakening in this case is a result of future land interaction, not necessarily regional climatology. This storm is mapped in the hexagon 150 nautical miles from the coast, not where it moved to 24 hours later and shows a storm losing 60 knots of intensity.

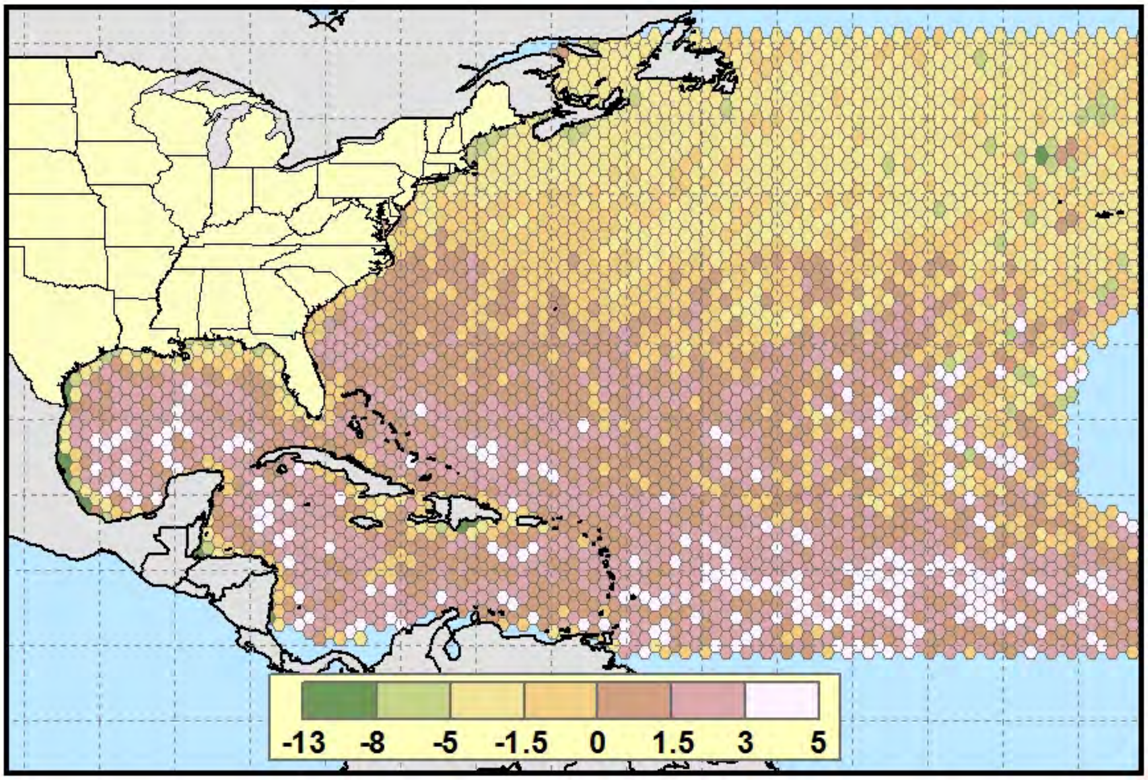

Figure 4.18 The average change in intensity (knots) for the 6 hour period of storms in the North Atlantic Basin passing through equal area hexagons. Period of record is 1851-2004.

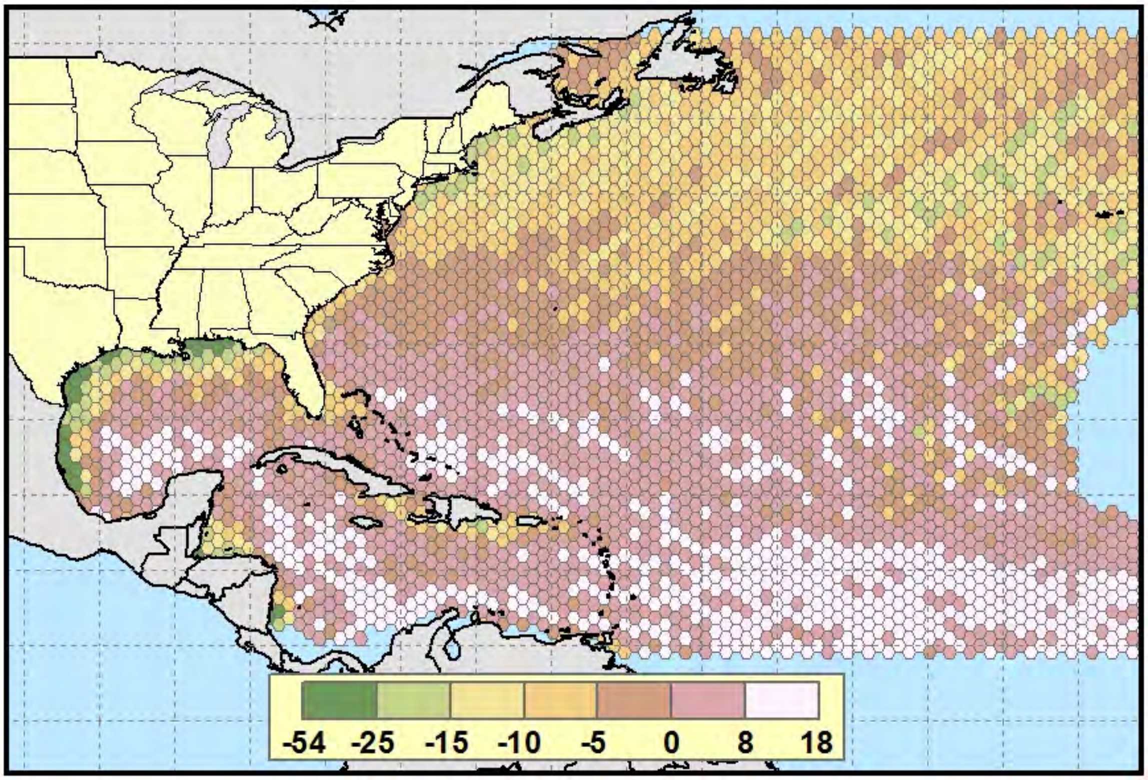

Figure 4.19 The average change in intensity (knots) for the 24 hour period of storms in the North Atlantic Basin passing through equal area hexagons. Period of record is 1851-2004.

CHAPTER 5

ANALYSIS

The analysis of maps displayed in Chapter 4 is essentially an exercise in synoptic climatology; i.e., an attempt to describe and explain large-scale atmospheric patterns (Court 1957). These synoptic scale atmospheric features dictate the movement of tropical cyclones in all portions of the Atlantic Basin (Helm 1967). An analysis of the dominant pressure and wind patterns over various lengths of time explains a large portion of the variation in movement of tropical cyclones.

Subtropical High Pressure Cell

The semi-permanent subtropical high pressure cell in the Atlantic Ocean is the primary forcing mechanism for tropical cyclone movement. This high pressure cell has been referred to in the plural as the Azores and Bermuda Highs. In reality, this is a single atmospheric feature (Miyasaka and Nakamura 2005). The western portion of the subtropical high pressure cell is colloquially called the Bermuda High. Winds rotate clockwise around high pressure cells in the Northern Hemisphere; therefore, knowing the position and intensity of the subtropical high pressure cell enables a climatological assessment of historical wind direction - the primary contributing factor for tropical cyclone movement (Dong and Neumann 1986; Aguado and Burt 2004).

The National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) publish a digital collection of global atmospheric data based on a 2.5^o x 2.5^o worldwide grid (Kalnay et al. 1996). The data are obtained from a combination of satellite, rawinsonde, model output, ship, aircraft, and land-based observations. The data set contains continuous observations for 100 variables at 28 levels of the atmosphere from 1948 to the present time. Maps of any variable are automatically generated by utilizing an interactive mapping application available through the Internet.

The data displayed in Figures 5.1 through 5.6 were generated using the NNEP/NCAR online mapping application. Figure 5.1 shows the mean sea level pressure for the Atlantic Basin from 1948 through 2004. Figures 5.2 and 5.3 show the mean sea level pressure for the summer months of 2003 and 2005 respectively. Finally, Figures 5.4 through 5.6 show the geopotential height of the 700 millibar surface for the same time periods as Figures 5.1 through 5.3.

Sea Level Air Pressure

A map of average sea level pressure displays the surface extent of the subtropical high pressure cell in the Atlantic Ocean. Figure 5.1 shows the average surface pressure for all days of the year between 1948 and 2004. The area of highest pressure is centered south and southwest of the Azores; hence the term, “Azores High.” The axis of highest pressure extends westward along 30^{o}N into the southeastern United States; this portion of the subtropical high pressure cell is called the “Bermuda High.”

The entire Atlantic Basin south of 25^{o}N lies along the southern periphery of the subtropical high. Since the air flow around high pressure cells in the Northern Hemisphere is clockwise, winds generally move from east to west; an area also known as

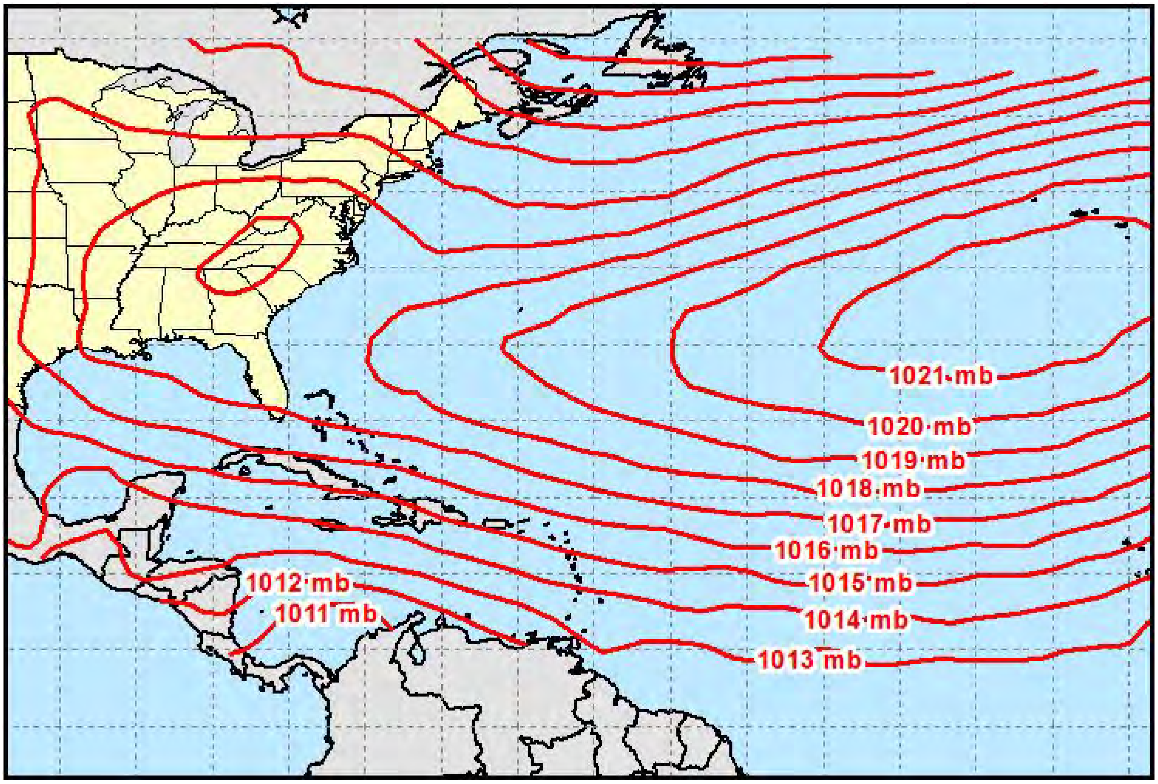

Figure 5.1 Average sea-level pressure for the Atlantic Basin between 1948 and 2004 (Kalnay et al. 1996).

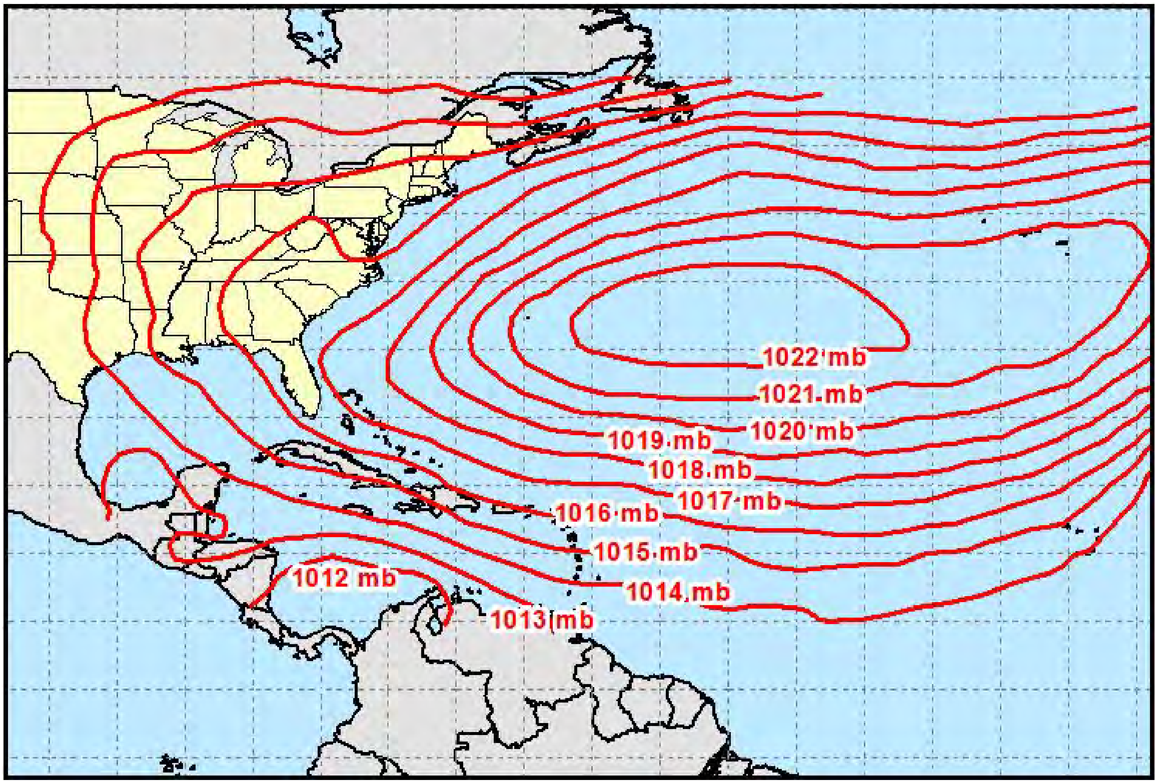

Figure 5.2 Average sea-level pressure for the Atlantic Basin between June 1, 2003, and September 30, 2003 (Kalnay et al. 1996).

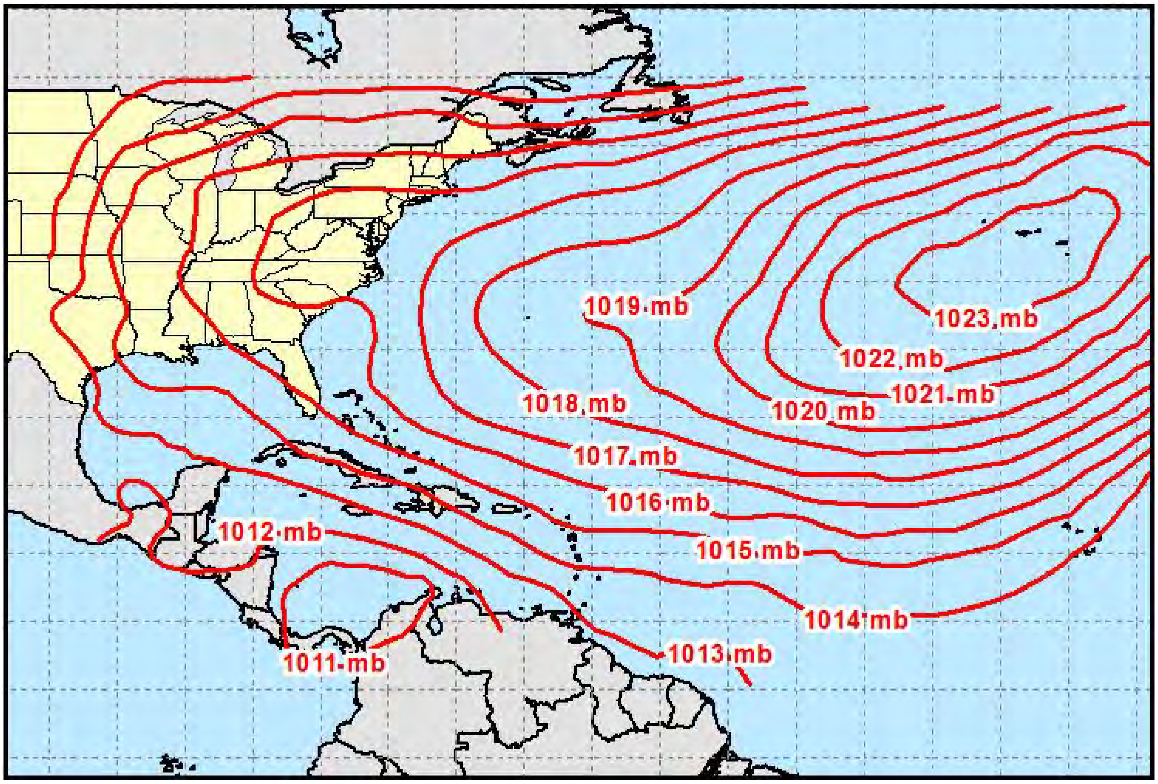

Figure 5.3 Average sea-level pressure for the Atlantic Basin between June 1, 2005, and September 30, 2005 (Kalnay et al. 1996).

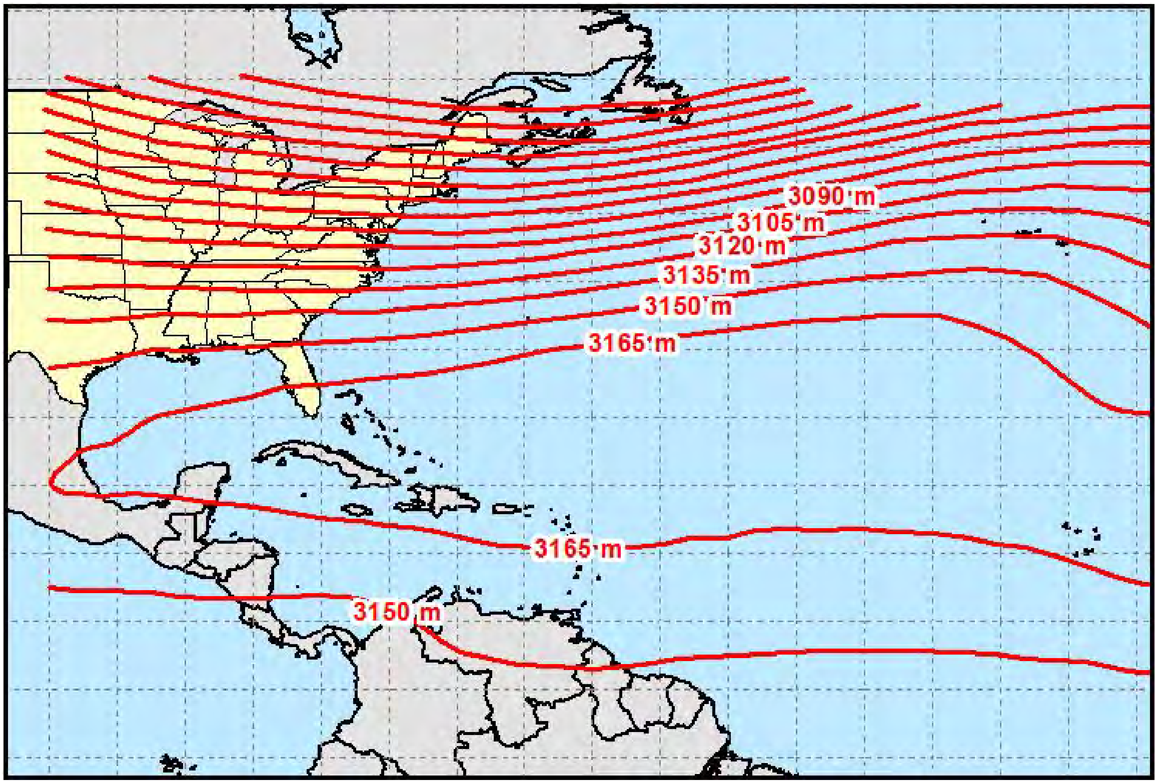

Figure 5.4 Average height for the Atlantic Basin from the surface to 700 millibar level between 1948 and 2004 measured in meters (Kalnay et al. 1996).

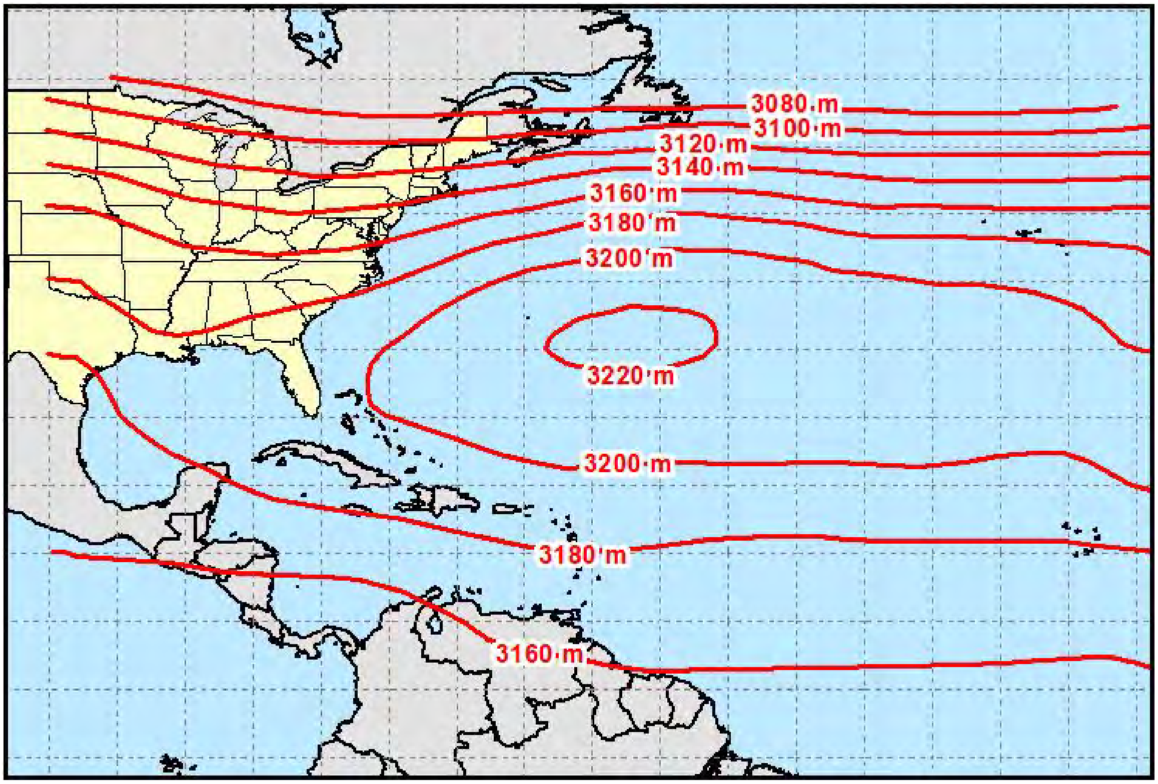

Figure 5.5 Average height for the Atlantic Basin from the surface to 700 millibar level between June 1, 2003, and September 30, 2003 measured in meters (Kalnay et al. 1996).

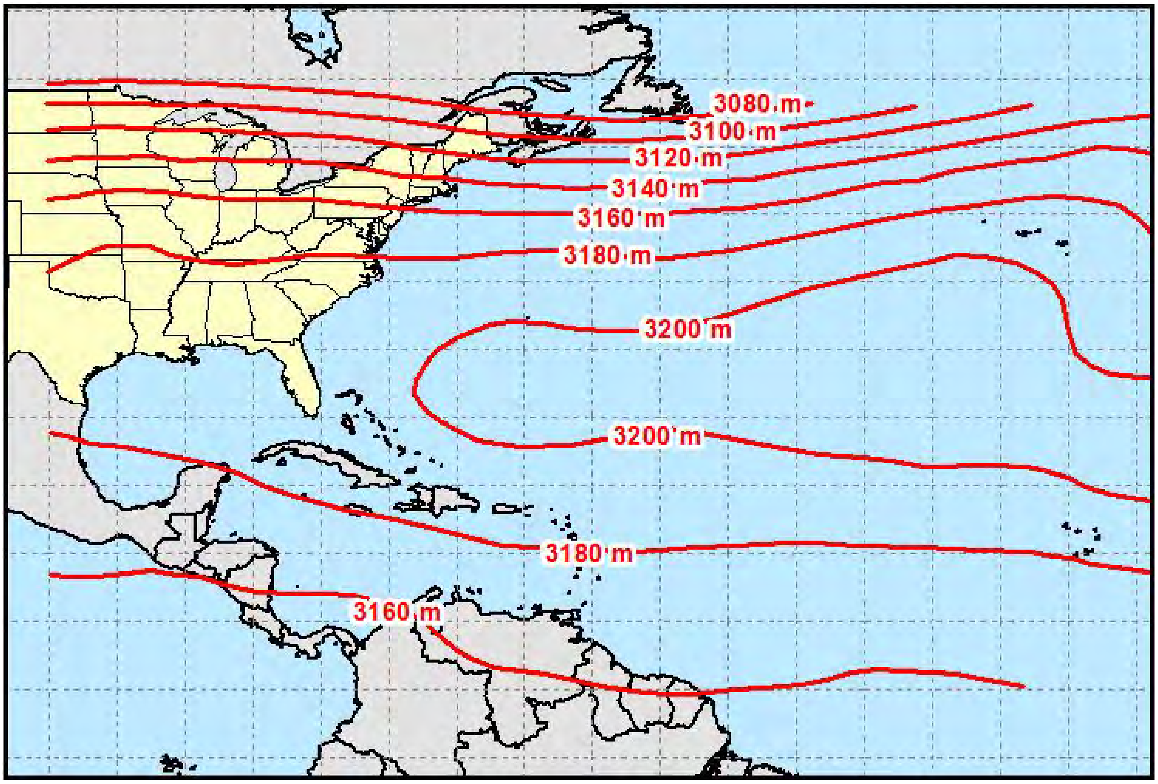

Figure 5.6 Average height for the Atlantic Basin from the surface to 700 millibar level between June 1, 2005, and September 30, 2005 measured in meters (Kalnay et al. 1996).

the “tropical easterlies”. This portion of the Atlantic Basin is where storms usually move in a westerly or west-northwesterly direction (see Figure 4.2).

Figure 5.1 shows the sea level pressure for the entire year; however, the pattern during the summer months is slightly different and varies from year to year. Figure 5.2 shows the sea level pressure during June, July, August, and September of 2003. During this period, the center of the high pressure cell was near 35^{o}N and 55^{o}W; slightly east of Bermuda. The position of the subtropical ridge during this summer period is shifted south and west of the long-term average position measured for all months of the year.

The position of the subtropical high pressure cell in 2005 was substantially different than in 2003. Figure 5.3 shows the average sea level pressure during the summer months of 2005. The pressure regime in 2005 was considerable stronger and centered over the Azores. Near the island of Bermuda, the average sea level pressure in 2003 was 1021 millibars and in 2005 it was 1018.5 millibars. Near Miami, Florida, the average sea level pressure in 2003 was 1016.5 millibars and in 2005 it was 1015 millibars. At these two locations, the orientation of the isobars was nearly identical in the two sample years; however, many locations experienced isobars with different orientations. The orientation of the isobars and the difference in pressure gradient are significant factors in explaining variations in storm tracks at similar geographic locations for different years.

Upper Level Heights

Dong and Neumann (1986) reviewed upper level wind patterns in the vicinity of tropical cyclones to determine the level at which winds exert the maximum steering influence. Their work showed that specific steering currents affecting tropical cyclones are dependent on the latitude and the intensity of the storm. Tropical storms are steered predominantly by winds at 700 millibars while hurricanes are steered by winds at 400 to 500 millibars. The primary steering level is slightly different depending on which side (north or south) of the subtropical ridge the storm resides. The NCEP/NCAR online mapping application does not contain wind vectors at the current time; nor does it contain pressure values for constant elevations. However, it does contain geopotential heights for many constant pressure surfaces. Since the 700 millibar level is important for tropical cyclone movement, particularly for tropical storms (<65 knots), a historical perspective of this pressure level is important to understanding tropical cyclone movement.

Figure 5.4 shows the 700 millibar geopotential height for the period from 1948 through 2004. The patterns for this pressure level are not as clearly defined as for sea level. The variation between summer and winter is great enough to distort the seasonal trends. However, a north-south trough axis is evident along the East Coast of the United States and a northeast to southwest ridge axis exists between the Azores and the central Atlantic near 25°N and 55°W. This pattern broadly suggests that the trough of low pressure along the East Coast promotes recurvature of storms prior to U.S. landfall.

An analysis of the 700 millibar geopotential height during the summer seasons of 2003 and 2005 reveals a clearer pattern of steering flows compared to the annual average. Figure 5.5 shows the 700 millibar height for June, July, August, and September of 2003. The highest height, which is a proxy for the highest pressure regime, is southeast of Bermuda. The clockwise flow around the high pressure forces tropical cyclones south of the high pressure to move west and storms north of the high pressure to move east. A trough of low pressure is evident from the eastern Great Lakes region to New Orleans. This trough promotes recurvature immediately to the east of the trough's axis.

By comparison, the 700 millibar geopotential height for the summer of 2005 reveals a somewhat different pattern. The ridge is slightly stronger, farther east, and flatter than in 2003. Also, there is no semi-permanent trough along the eastern portion of the United States. Without a trough, storms south of the subtropical ridge are more likely to strike the East Coast of the U.S.

The sea level air pressure and 700 millibar geopotential height vary on a daily, seasonal, and annual basis. However, the variation is only characterized by changes in the strength and location of the subtropical ridge; not its presence or lack thereof. The subtropical high pressure cell is always present in the Atlantic Basin. Storms that are south of the high pressure cell move westward and storms that are north of the high pressure cell move eastward. Therefore, the storm tracks shown in Figure 2.1 are a proxy measure of the position and strength of the subtropical high pressure cell.

In Chapter 4, twelve different states and regions were assessed for their tropical cyclone landfall probabilities. These states and groupings were selected because state governments are responsible for emergency planning, evacuations, and many other aspects of disaster preparation and response. Synoptic climatology, which dictates general movement of storms, does not follow political boundaries. Therefore, a different grouping of states is used to identify storm movement patterns during the historical period of record. These groupings are affected by different components of the synoptic climatology system. The next five sections describe these synoptic regimes and several representative storms are provided for each section.

Texas and Louisiana Storm Analysis

The region of the Atlantic Basin where storms affecting Texas and Louisiana originate and traverse is very similar to the 1016 and 1017 isobars in Figure 5.1with one significant difference. Storms in the far eastern Atlantic Basin rarely strike Texas or Louisiana. If a storm is east of the Lesser Antilles, any weakness in the subtropical ridge will cause the storm to move to a higher latitude. Once the latitude of a storm increases, there is no usual mechanism to force the storm to move with any southerly component. Therefore, only a consistently strong subtropical ridge enables a storm to cross the entire Atlantic.

Figure 5.7 shows a small sample of climatologically representative storms that impacted Texas or Louisiana. Hurricane Audrey in 1957, Hurricane Allen in 1980, and Hurricane Lili in 2002 each made landfall in either Texas or Louisiana. Hurricane Audrey represents the typical storm moving northward through the central/eastern Gulf of Mexico before making landfall. Hurricanes Allen and Lili are typical of storms moving through the southernmost Lesser Antilles and eventually moving through the Yucatan Channel prior to U.S. landfall.

A sharp distinction exists between storms moving across the eastern and western portion of the Yucatan Channel (see Figures 4.4 and 4.5). Along the eastern portion of the channel, Texas is a likely target. Louisiana is a likely target for storms passing through the western portion of the channel.

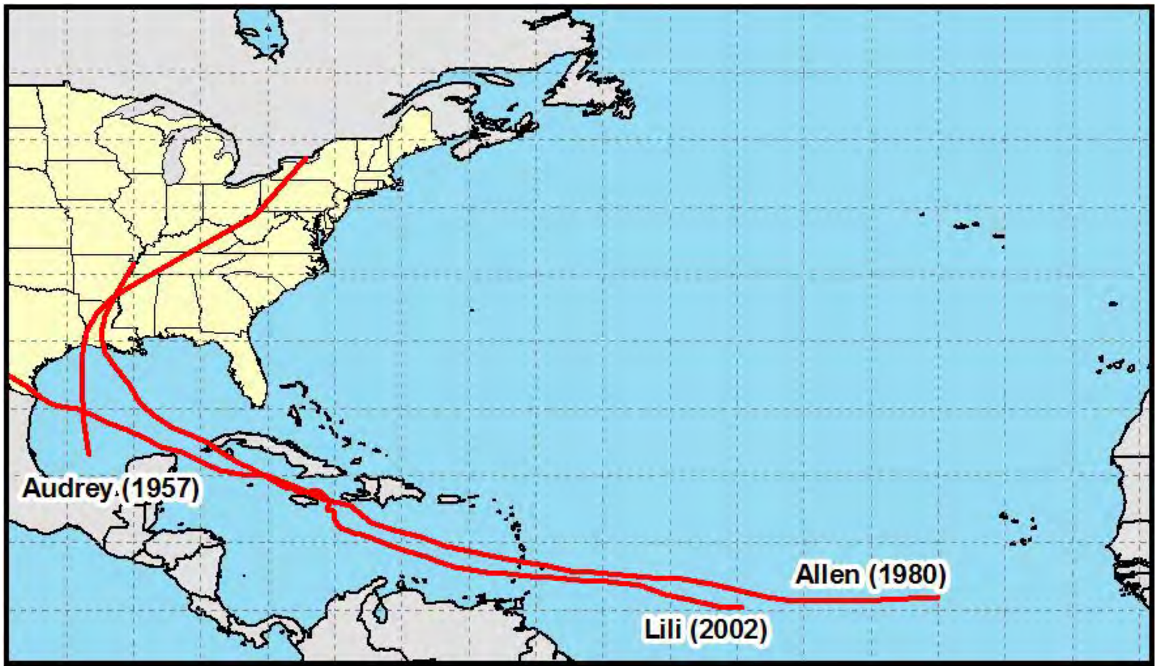

Figure 5.7 Several representative storms and their tracks for the Texas and Louisiana regions.

Eastern Gulf Coast Storm Analysis

The region of the Atlantic Basin contributing storms affecting the eastern portion of the Gulf coast is noticeably different than the region contributing storms affecting Texas or Louisiana. Storms that traverse the central Atlantic Ocean at slightly higher latitudes than those that strike Texas or Louisiana ultimately impact the western coast of Florida, Alabama, and Mississippi.

Figure 5.8 shows a small sample of climatologically representative storms that impacted the eastern Gulf coast. Hurricane Frederic in 1979 is an example of a long-track, “Cape Verde” storm that made landfall while traveling in a northwesterly direction. Frederic impacted the northern Lesser Antilles as opposed to the southern Lesser Antilles, whose storms commonly affect Texas or Louisiana. The southwestern Caribbean Sea is a frequent contributor of storms impacting this region (see Figure 4.16). Hurricane Alma in 1970 demonstrates a typical storm track through this area. Hurricane Opal in 1995 is an example of a storm forming in the Gulf of Mexico and traveling northward toward this region.

Storms crossing the Florida peninsula (not shown in Figure 5.8) frequently make a second landfall in this region. These storms often (but not always) lose considerable strength wile crossing land before re-emerging over the Gulf of Mexico.

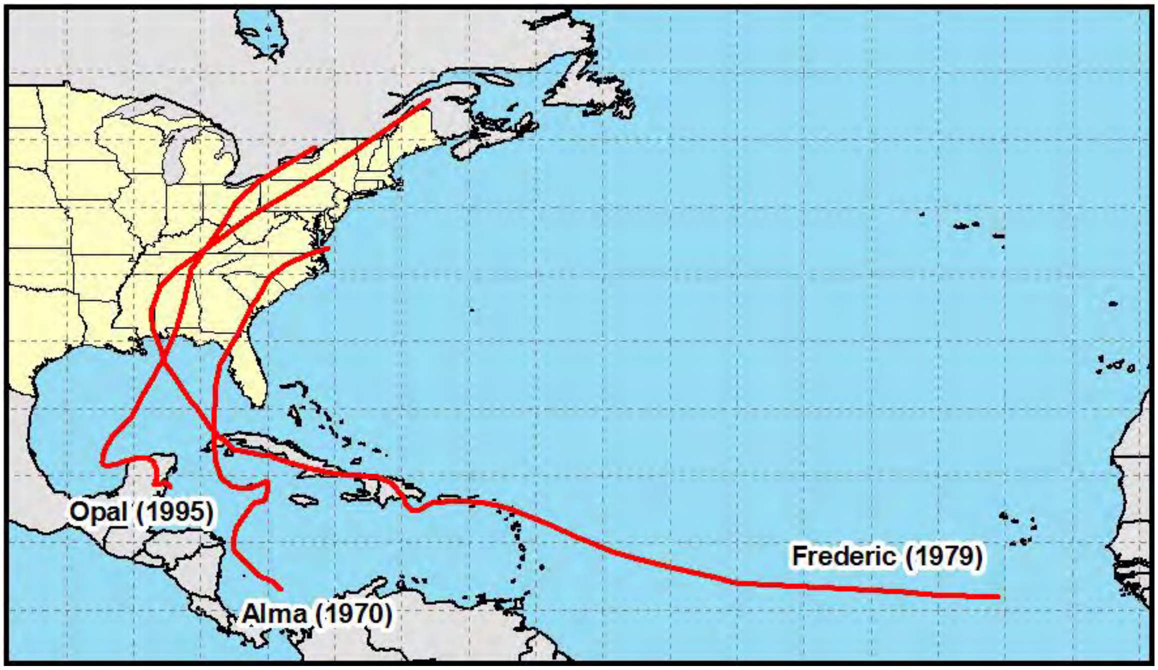

Figure 5.8 Several representative storms and their tracks for Mississippi, Alabama, and the west coast of Florida.

Eastern Florida Coast to South Carolina Storm Analysis

Storms moving through the Bahamas are candidates for future landfall along the east coast of Florida, Georgia, and South Carolina. A majority of storms impacting the east coast of Florida move in a northwesterly direction; unlike the westerly direction of Hurricane Andrew in 1992. Most landfalling storms in this region are in the recurvature stage of their life cycle.

A sharp surface pressure gradient is apparent in Figure 5.1 between the southern tip of Florida and North Carolina. This defines the western extent of the semi-permanent Bermuda High pressure region. South of southern Florida, the steering flow is west-northwest. North of this region, the steering flow abruptly becomes northerly and even northeasterly during certain portions of the hurricane season.

Figure 5.9 shows a small sample of climatologically representative storms that impacted the east coast of Florida, Georgia, and South Carolina. Many of these storms form in the far eastern Atlantic Ocean and pass near Puerto Rico and the Bahamas before making landfall. The storms that traverse long stretches of the open ocean before striking land are often very intense. A second category of landfalling storms form in the Gulf of Mexico and cross the Florida Peninsula before making a second landfall in Georgia or South Carolina.

Many storms impacting this region arrive from the Florida panhandle (not shown) and cross Georgia and South Carolina as decaying tropical cyclones. While locally significant, these storms are less spatially predictable since they may form in the deep tropics or may form just prior to landfall in the Florida panhandle.

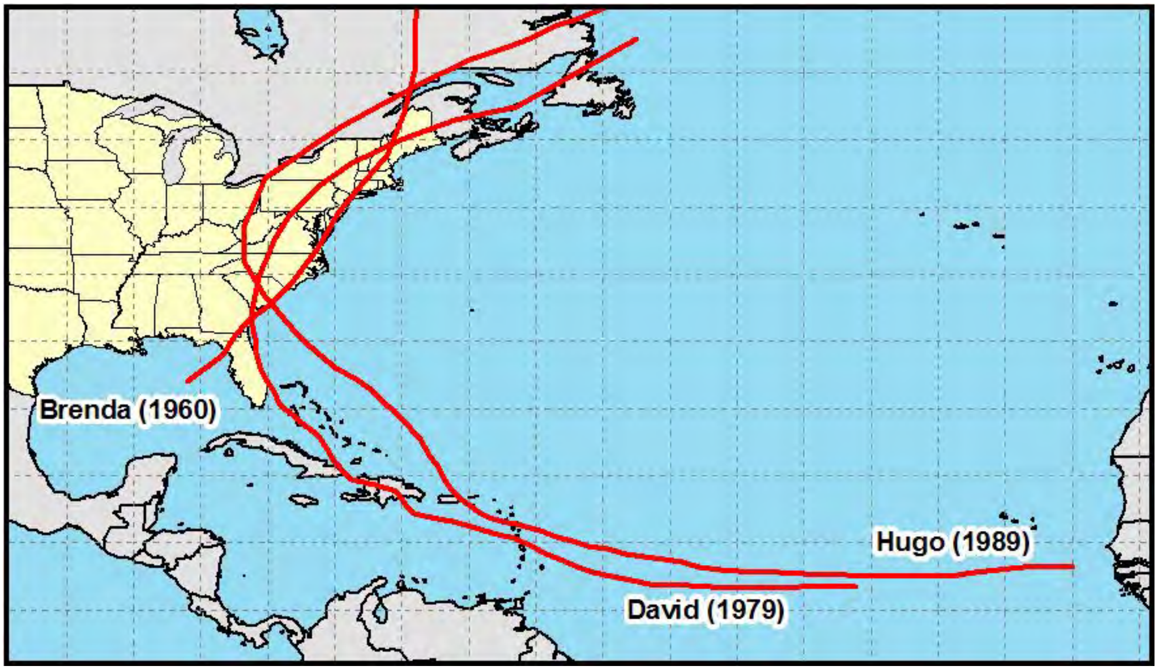

Figure 5.9 Several representative storms and their tracks for the east coast of Florida, Georgia, and South Carolina.

North Carolina to New Jersey Storm Analysis

Two classes of storms impact North Carolina, Virginia, Maryland, Delaware, and New Jersey. The first class of storms brushes the North Carolina Outer Banks. The second class of storms initially strike elsewhere in the southeastern Unites States and crosses the remainder of the region as a weak tropical cyclone.

Figure 4.3 shows the overall storm density in the Atlantic Basin. The area immediately east of the North Carolina coast contains the highest overall concentration of storms in the Atlantic Basin. When the subtropical high pressure cell is slightly stronger than average, storms are deflected slightly farther west over inland North Carolina.

Coastal North Carolina is north of the latitude of the strongest portion of the subtropical ridge and therefore storms usually move northeast at that longitude. A modest northward shift of the ridge forces storms to move in a northerly direction in the vicinity of North Carolina. Once these northward moving storms make landfall in North Carolina, they continue north toward the Delmarva peninsula and New Jersey as they weaken. The storms north of the North Carolina/Virginia state line only rarely exist at hurricane strength.

Figure 5.10 shows a small sample of climatologically representative storms that impacted North Carolina, Virginia, Maryland, Delaware, and New Jersey. Most of these storms form in the far eastern Atlantic Ocean and pass north of the Bahamas before making initial landfall in North Carolina and continuing to the other states in this grouping.

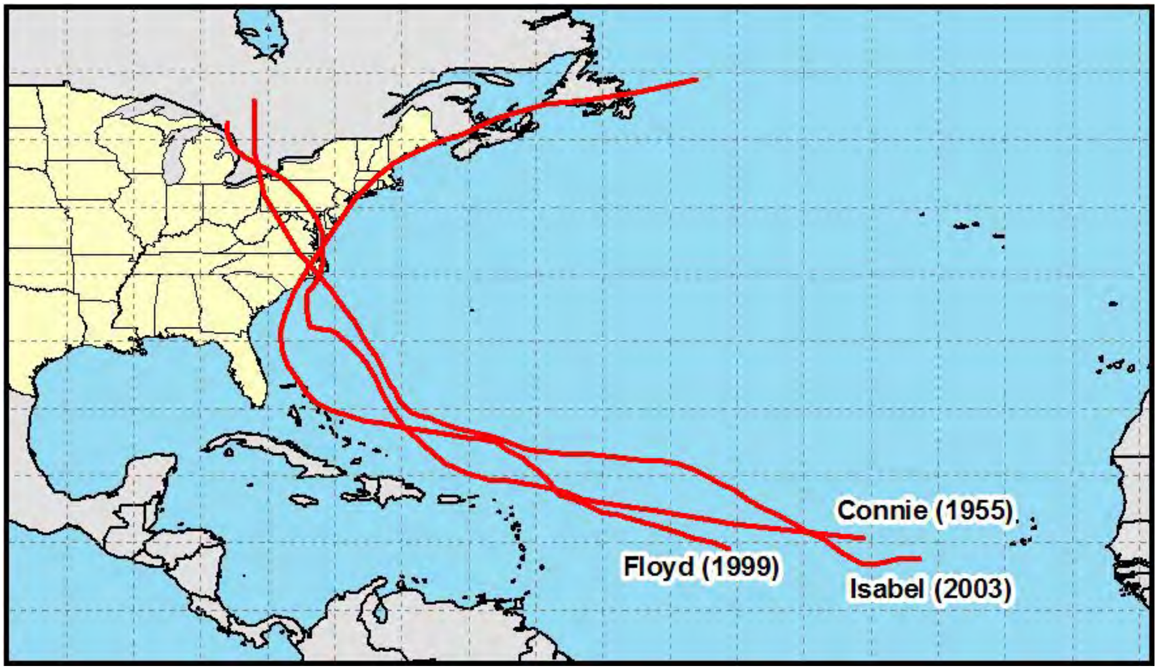

Figure 5.10 Several representative storms and their tracks from North Carolina to New Jersey.

New York to Maine Storm Analysis

The New York and New England states are infrequently impacted by strong tropical cyclones. When storms strike this region, they often are undergoing extratropical transition and/or moving at a fast forward speed. The latitude of this region places it well north of the subtropical ridge axis; therefore, storms normally move northeast or even east at the latitudes of New England. When the subtropical ridge is shifted farther north, storm recurvature is delayed long enough for landfall to occur in this region. Figure 5.5 shows the semi-permanent summer trough of low pressure in the upper atmosphere that normally causes recurvature.

Figure 5.11 shows a small sample of climatologically representative storms that impacted New York, Connecticut, Rhode Island, Massachusetts, New Hampshire, and Maine. Each of the three storms achieves a greater longitude (farther west) than is normally expected at high latitudes when they approach the coast of the United States. Most storms impacting this region form in the central or eastern Atlantic Ocean. Only a few storms that developed in the Gulf of Mexico eventually impacted this region; and only as tropical storms – not hurricanes.

The famous "Long Island Express" storm of 1938 and Hurricane Gloria both struck Long Island in New York state before impacting the rest of the states in New England. In fact, nearly all storms crossing one New England state affect all other states in the region. The one exception is when storms track across the Cape Cod portion of Massachusetts. Several of these storms did not impact any other state other than Massachusetts.

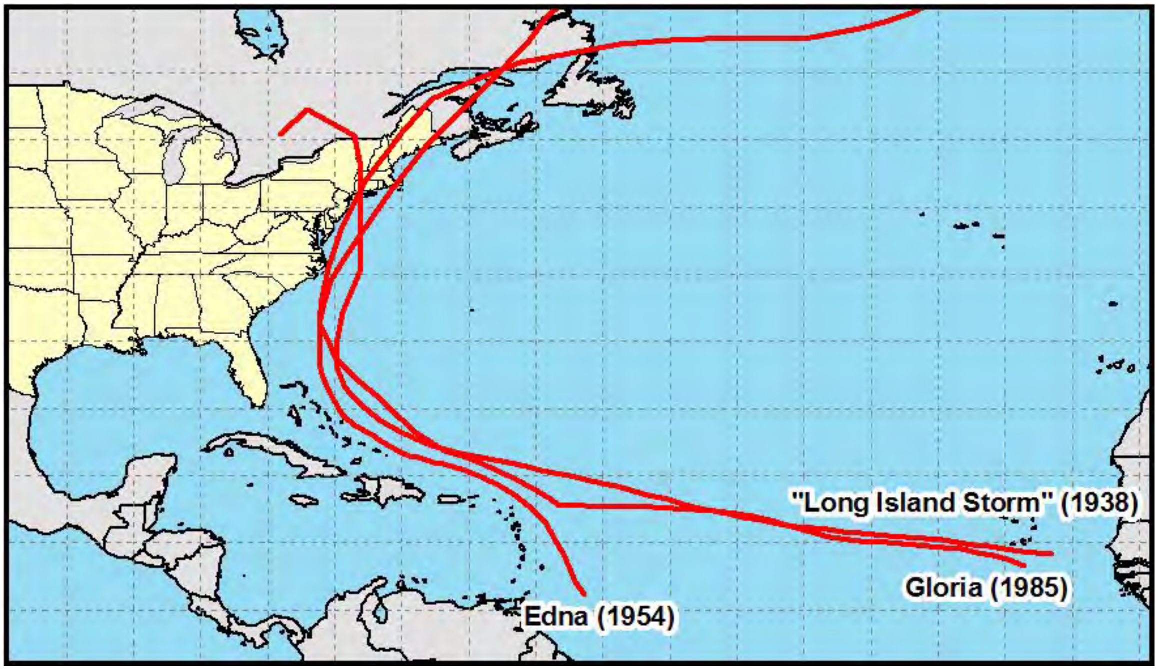

Figure 5.11 Several representative storms and their tracks from New York to Maine.

Intensity Change Analysis

The change in tropical cyclone intensity is a function of the following three factors: 1) interaction with land, 2) upper level wind shear, and 3) sea surface temperatures (Fitzpatrick 2005). The interaction with land is straightforward when the land mass is continental. However, interaction with the islands of the Greater Antilles is highly variable due to the uneven distribution of mountainous terrain. The intensity maps in Figures 4.18 and 4.19 show the significant effect the island of Hispaniola exerts on tropical cyclones compared to Cuba or Jamaica. Hispaniola contains very rugged terrain which causes significant wakening of storms passing over the island. The standard weakening rate is a decrease of ½ the wind speed every 12 hours over land.

Figures 5.4 through 5.6 illustrate pressure patterns in the upper atmosphere, thereby showing wind speed. The geopotential height isohypses south of 25^{o}N are spaced far apart indicating relatively small pressure gradients; therefore slow wind speeds. Storms in this region of the Atlantic Basin historically intensify (see Figures 4.18 and 4.19). Storms at higher latitudes experience stronger winds in the upper atmosphere as indicated by the tightly spaced geopotential height isohypses. This increase in wind shear prevents tropical cyclones from intensifying.

The primary factor supporting or inhibiting storm intensification is ocean heat content (Lauber 1996; Stull 2000). Tropical cyclones require ocean temperatures above 80^{o}F. Figure 5.12 shows the average sea surface temperature during the months of July, August, and September, for the North Atlantic Ocean (NODC 2004). The higher the water temperature is above the minimum threshold, the more energy is available for the storm to utilize.

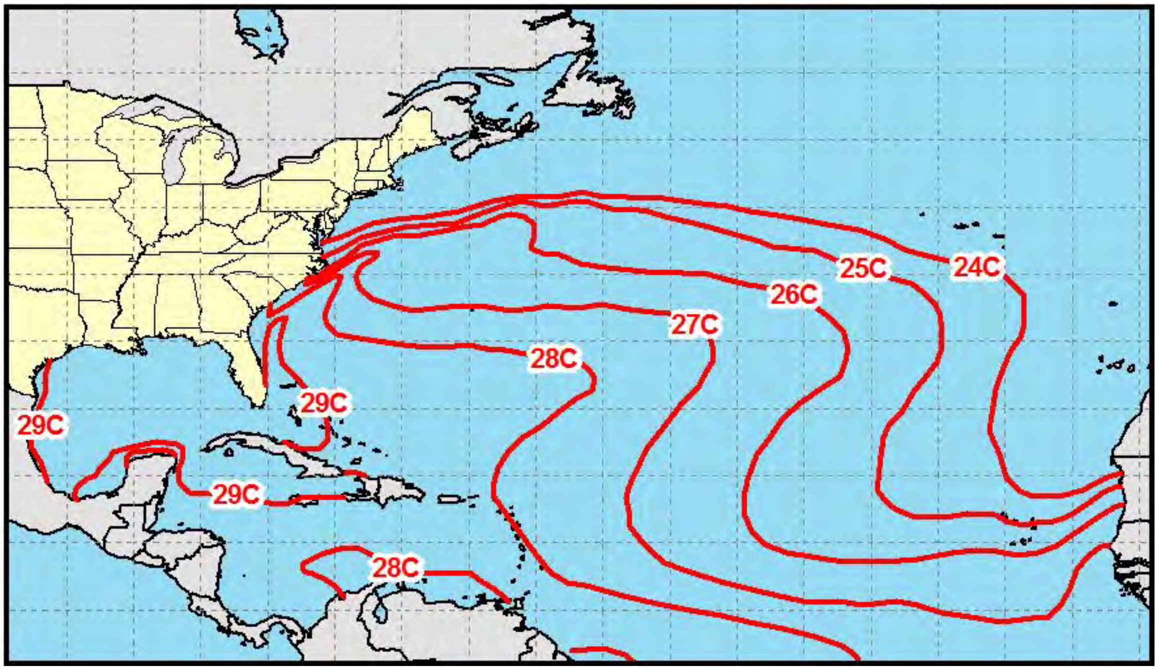

Figure 5.12 Average sea surface temperature isotherms for the months of July, August, and September measured between 1985 and 2001 (NODC 2004).

Days From Landfall Analysis

The time until landfall is a function of distance from land and forward speed. The distance from land is dependent on the exact track that a storm follows. For example, a hypothetical storm at the western end of Puerto Rico is 835 nautical miles (nm) from Miami, Florida. However, the distance to Long Island, New York, is 1,350 nm and the distance to Galveston, Texas, is 1,630 nm. Assuming the storm is moving at 15 knots, a trajectory toward Miami, Florida, implies a landfall in 2.3 days. A trajectory toward Long Island, New York, implies a landfall in 3.75 days and a trajectory toward Galveston, Texas, implies a landfall in 4.5 days. Therefore, the average time until landfall (see Figure 4.17) for the hypothetical storm near Puerto Rico is highly uncertain. However, the variability of movement of storms in different portions of the Atlantic Basin is substantially different. Storms south of 15^{o}N and east of 50^{o}W nearly always move from east to west or east-southeast to west-northwest; very few storms in this region move in a different direction. In contrast, storms in the central Gulf of Mexico frequently move east, west, or north. A storm that is 100 nm west of Florida will strike land in a few hours if moving east or northeast; however, it will take several days to strike Texas if moving westward.

The other portion of the length until landfall equation is the forward speed of tropical cyclones in different portions of the Atlantic Basin. Figure 5.13 shows the average speed of movement for all tropical cyclones during the historical period (not just landfalling storms). Since storms at higher latitudes generally move faster, the isocrones of equal time until landfall are farther away from the coastline for the New England states than for Texas or Louisiana.

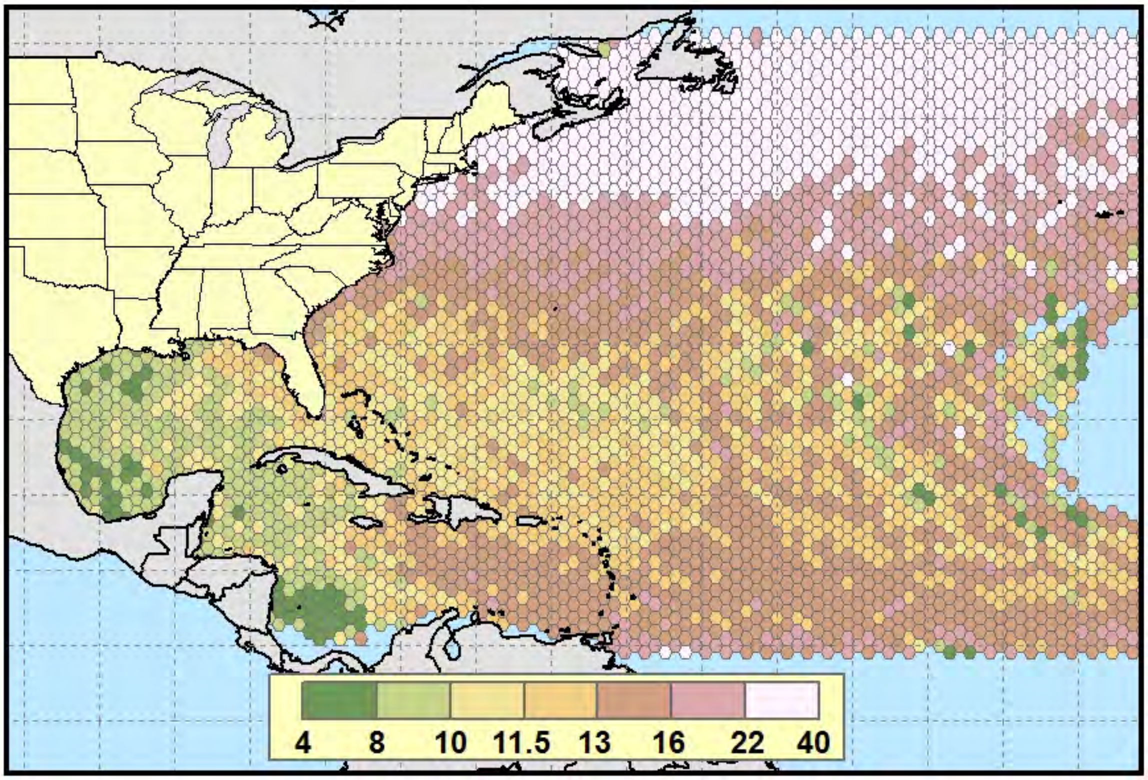

Figure 5.13 Average forward movement of storms passing through equal area hexagons (measured in knots). Period of record is 1851-2004.

Comparison of 2005's Major Storms With Climatology

The four major hurricanes (100+ knot winds at landfall) traveled across areas with varying degrees of historical landfall probability. The purpose of this dissertation is to add a new measure of tropical cyclone landfall prediction. How did these four storms compare with the expected probability patterns described earlier in this chapter?

To assess the climatological point of view, each storm is viewed from the perspective of the states it impacted or was forecasted to impact as a major hurricane. For example, Hurricane Rita struck at the Texas/Louisiana border. Rita's complete storm track is examined and compared to the probability values for Texas (Figure 4.4). A second assessment is conducted to compare the complete storm track with the probability values for Louisiana (Figure 4.5). The two assessments are then overlaid on each other.

Figure 5.14 shows the tracks of the four storms (Hurricane Dennis, Hurricane Katrina, Hurricane Rita, and Hurricane Wilma) that made landfall in the United States. Only the point of landfall as a major hurricane is considered. Therefore, Hurricane Katrina's landfall in Florida as a Category 1 storm is not evaluated.

A surfacing technique was applied to the hexagon centroids to create a continuous raster grid of probability values for each of the states assessed as part of this section (not shown). A cross-section profile of the raster grid shows the historical landfall probability. The x-axis on the figures represents distance from landfall along the storm path – not the straight-line distance.

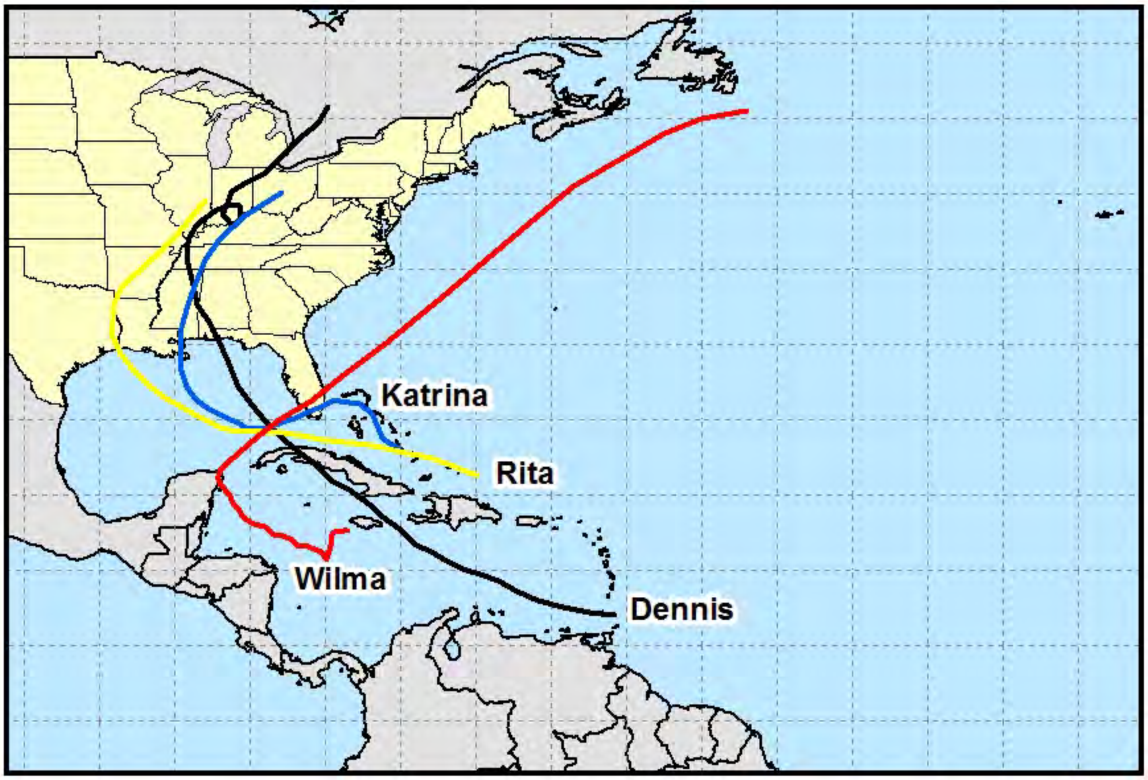

Figure 5.14 The four hurricanes of 2005 that made landfall in the United States at Category 3 or above intensity (100+ knots).

Hurricane Dennis (2005) Compared to Climatology

Hurricane Dennis formed in the vicinity of the southern Lesser Antilles near the island of Tobago. The storm moved in a northwesterly direction for 6.5 days until it made landfall near Destin, Florida (just east of the Florida/Alabama state line). The chart in Figure 5.15 shows the historical landfall probability during the entire history of Dennis until landfall. The blue line represents the landfall probability for Alabama, the green line represents the landfall probability for Florida, and the red line represents the probability for the Mississippi, Alabama, and Florida peninsula region described earlier.

When Dennis initially formed, the Mississippi, Alabama, and Florida panhandle region already showed a 30% chance of landfall based on the historical record. The first 1,000 nautical miles (nm) the storm traveled showed none of the states/regions gaining landfall probability; in fact, a slight decrease in landfall probability is observed indicating a lowering of historical landfall likelihood for several days after origination. Approximately 750 nm from landfall, the landfall probabilities begin to increase dramatically – except for Alabama.

The probability hexagons for Alabama (see Appendix C) are small in comparison to Florida. The landfalling likelihood for Florida spiked at 450 nm prior to landfall, dipped somewhat, and increased again until landfall. Florida's landfall probability is greater than 50% for the last 600 nm of the storm's track. The Mississippi, Alabama, and Florida panhandle region's probability did not exceed 50% until the final 200 nm of the storm's track. Alabama's landfall probability did not exceed 50% until the last 50 nm before landfall.

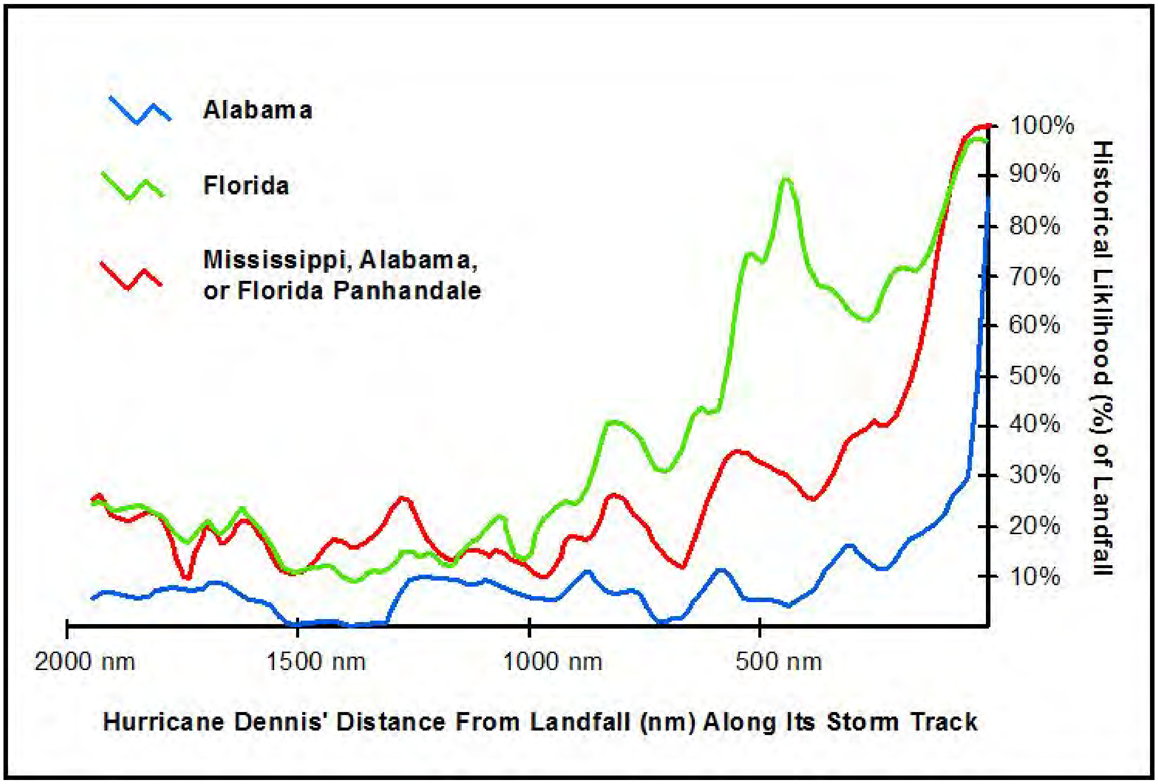

Figure 5.15 Historical landfall probability for Alabama, Florida, and the combined group of Mississippi, Alabama, and the Florida panhandle along the complete storm track of Hurricane Dennis in 2005.

Hurricane Katrina (2005) Compared to Climatology

Hurricane Katrina formed in the vicinity of the southeastern Bahamas. The storm moved in a northwesterly direction across the Bahamas and turned westward prior to landfall in southern Florida as a minimal hurricane. Katrina moved southwesterly upon entering the Gulf of Mexico before turning northwest and finally northward between 85^{o}W and 90^{o}W.

The chart in Figure 5.16 shows the historical landfall probability during the entire 6.75 day history of Katrina until landfall at the Louisiana and Mississippi border. The blue line represents the landfall probability for Alabama, the green line represents the landfall probability for Louisiana, the red line represents the landfall probability for Mississippi, and the yellow line represents the landfall probability for Texas.

Katrina formed in a region where few storms ultimately impact either Louisiana or Mississippi. Neither of the landfall probabilities for Louisiana or Mississippi exceeded 10% until the storm was 450 nm from the coast in the central Gulf of Mexico. As recently as 250 nm before landfall, the landfall probability for Mississippi was 15% and the probability for Louisiana was only 25%. Texas' landfall probability was greater than that of Mississippi for nearly the entire history of Katrina.

The landfall probability for all the states did not match well with climatology until the last 450 nm of Katrina's track. The west and southwest motion of Katrina during the first three days of the storm were unusual and when the storm entered the central Gulf, Texas showed the highest landfall probability. Unlike Hurricane Dennis, the historical landfall >5 days in advance provided little benefit.

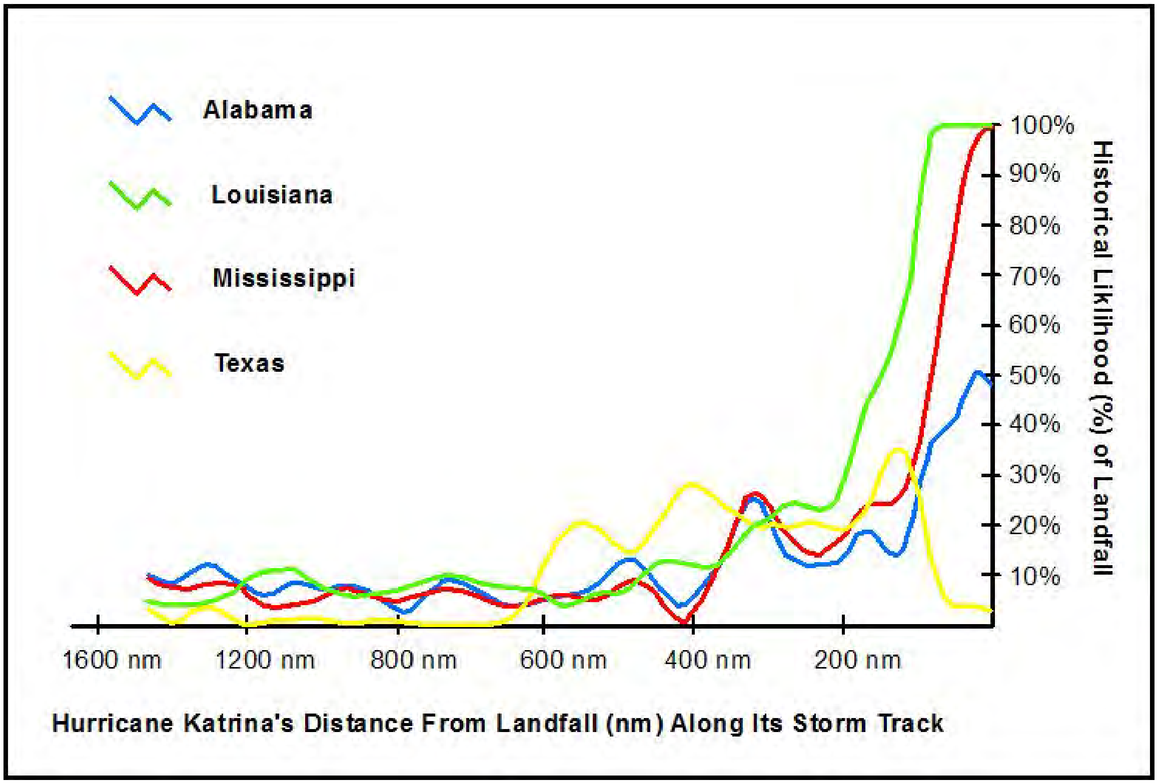

Figure 5.16 Historical landfall probability for Alabama, Louisiana, Mississippi, and Texas along the complete storm track of Hurricane Katrina in 2005.

Hurricane Rita (2005) Compared to Climatology

Hurricane Rita formed in a similar area as Hurricane Katrina several weeks earlier near the southeastern Bahamas. Rita immediately started on a west northwest track and did not veer much from that bearing until a northwest turn in the day prior to landfall.

The chart in Figure 5.17 shows the historical landfall probability during the entire 6.75 day history of Rita until landfall at the Louisiana and Texas border. The green line represents the landfall probability for Louisiana and the red line represents the landfall probability for Texas.

Neither state showed an initial landfall probability as high as 10%. Once the storm moved into the central Gulf of Mexico (about 1,000 nm prior to landfall), the historical landfall probabilities increased for both states. The Louisiana historical landfall probability starts low but increases steadily for the final 1,000 nm before Rita makes landfall. Texas' landfall probability increases to 25% at 1,000 nm and oscillates between 20% and 40% for the next 800 nm.

Once Rita came within 300 nm of landfall, the landfall probabilities increased dramatically for both states. Even though the earlier (eastern and central Gulf of Mexico) landfall probabilities are comparatively lower, they are higher for Texas and Louisiana than for any other state. Climatology performed much better for Hurricane Rita than for Hurricane Katrina. Interestingly, the forecasts for Rita when it was in the eastern and central Gulf of Mexico was for a landfall in southern or central Texas. Climatology suggested that the storm would turn poleward and it eventually did.

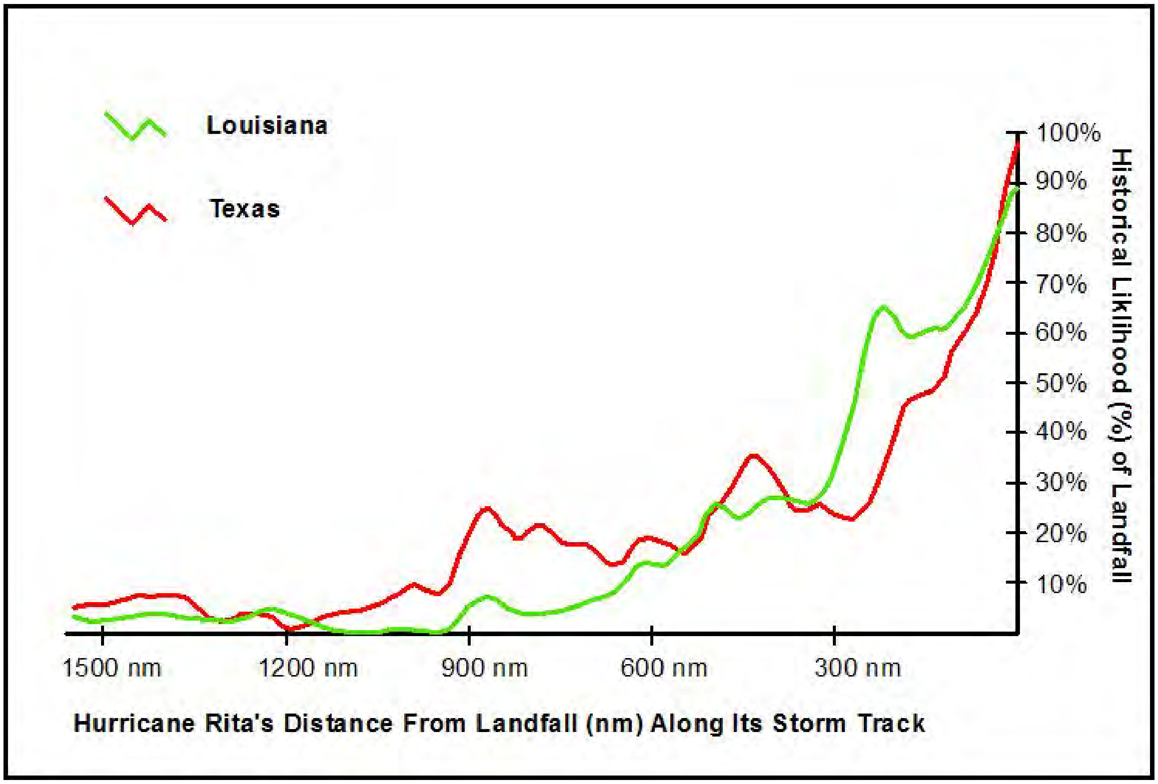

Figure 5.17 Historical landfall probability for Texas and Louisiana along the complete storm track of Hurricane Rita in 2005.

Hurricane Wilma (2005) Compared to Climatology

Hurricane Wilma formed in the vicinity of Jamaica. The storm initially moved in an erratic southerly direction before turning to the west-northwest. Before directly striking Cozumel, Wilma became the most intense hurricane on record in the Atlantic Basin (892 mb). After striking Cozumel and Cancun, Wilma turned to the northeast and accelerated toward Florida.

The chart in Figure 5.18 shows the historical landfall probability during the entire 9.25 day history of Wilma prior to landfall in southeastern Florida. The green line represents the landfall probability for Florida and the red line represents the landfall probability for Texas. Texas is included in the analysis because for a short period of time, Texas had a higher landfall probability than Florida.

For only one day in Hurricane Wilma's history was the eventual landfall probability less than 25% for the state of Florida. That one day was when Wilma passed over Cozumel and Cancun. That region contains high landfall probability hexagons for Texas and low landfall probability hexagons for Florida. Once Wilma turned to the northeast, the landfall probability for Florida went up dramatically and the probability for Texas dropped almost as dramatically. This is not surprising when looking at the average storm motion vectors in Figure 4.2.

The climatological performance of Hurricane Wilma making landfall in Florida was highly successful. Even when the storm originally formed and moved south, the Florida landfall probability did not decrease very much.

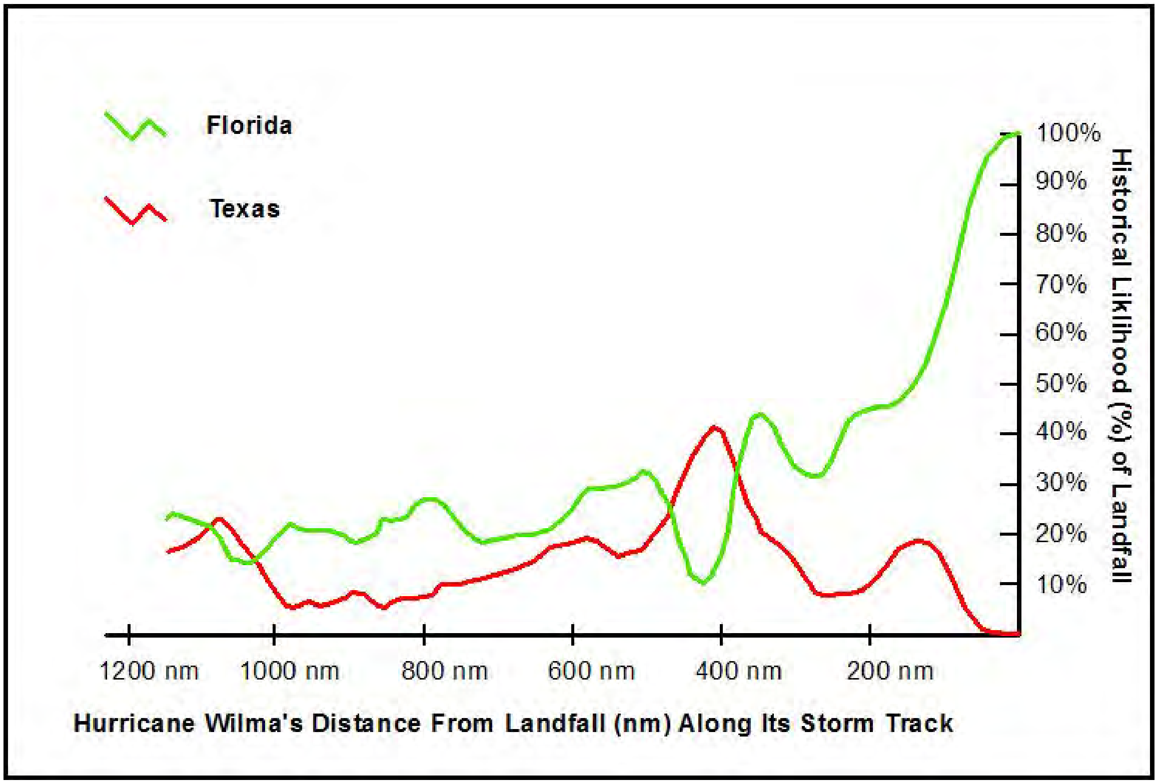

Figure 5.18 Historical landfall probability for Florida and Texas along the complete storm track of Hurricane Wilma in 2005.

CHAPTER 6

CONCLUSIONS

The maps of landfall probability presented in Chapter 4 are intended to provide a supplemental measure of preparedness to individuals and government entities along the Gulf of Mexico and Atlantic Ocean coastline. Contemporaneous forecasts are always superior to the historical record in the Atlantic Basin; however, the historical record is closely considered by computer models when estimating future storm movements and knowing the historical climatology enables a landfall prediction beyond the time frame of numerical forecasts.

Assessment of Results

A tessellation of 3,375 hexagons covering the Atlantic Basin enabled a systematic assessment of landfalling tropical cyclones for a 154-year period. A geographic information system determined the a posteriori probability of landfall based on the presence of storms passing through each of the hexagons.

The combined tracks of 522 landfalling storms (from 1,325 unique storms in the database) between 1851 and 2004 allow for the creation of baseline landfall probabilities. Table 4.1 shows the number of landfalling storms for each state or region. The total of landfalling storms in Table 4.1 is 1,324. Therefore, an average of 2.54 states are affected with each landfalling storm. The paths that these storms traverse is not random. There are known climatological factors that influence storm movement on all time scales. The maps in Chapter 4 clearly show the spatial regions that contribute storms to the different coastal states. Storms in various areas of the Atlantic Basin move in very predictable directions. The maps quantify these collective patterns.

Contributions

There are two major contributions this dissertation adds to the climatological research literature. First, a new dimension is added to the study of landfall probability. Current probability analysis assesses the likelihood of landfall for a county or state by comparing the total number of storms that made landfall and dividing by the length of the period of record. For example, 117 storms made landfall in Texas (83 different years) between 1851 and 2004. Therefore the annual probability of landfall for Texas is 0.54 (83/154). This assessment treats the Texas coastline as a one-dimensional feature (a line) and the reported results are temporally based; i.e., the annual threat of landfall.

This dissertation treats the Atlantic Basin as a two-dimensional tropical contribution zone. Instead of calculating the historical frequency of landfall, a series of two-dimensional sub-units of the Atlantic Basin (hexagons) are evaluated to determine if storms passing through those regions eventually make landfall somewhere in the United States.

Secondly, the methodological approach utilized for this dissertation is unique to the literature. Previous studies use large geographic contribution areas based on latitude and longitude coordinates. These contribution areas are not equal in size and therefore misrepresent the actual number of storms. This dissertation uses equal area hexagons to eliminate the spatial bias resulting from longitudinal convergence.

Future Research

Even though landfall probability values are quantitatively derived, the comparison of one state's probabilities with another state or region is qualitatively described. Spatial statistical techniques would yield additional information about the landfall correlation of adjoining states.

The geographic unit of landfall measurement is a state or grouping of states. The historical frequency of landfall is highly variable between the different states and regions. A data normalization technique to subdivide the coast into spatially equivalent geographical units based on frequency would result in cumulatively equivalent hexagon values and therefore expand the available analytical statistical techniques.

This dissertation creates a baseline landfall probability for twelve different states and regions for the complete period of record. Several well known oscillations (ENSO, PDO, NAO, etc.) exist that cause variations in the frequency and tracks of Atlantic Basin tropical cyclones. A comparison of storm tracks in years with strong positive or negative oscillation indices against the baseline values might yield interesting results.

Finally, comparison of landfall results based on different measurement shapes (square, circle, octagon, triangle, and hexagon) will enable empirically-based quantitative comparisons on ideal shape parameters; instead of theoretically based comparisons. In addition, the size of the shapes will influence the results. A shape that is too small will contain too few observations for analysis and shapes that are too large will over-generalize the data.

Final Thoughts

Each state and region along the Atlantic Basin coast is occasionally impacted by tropical storms and hurricanes. The region of origin and the portion of the Basin the storms traverse is not spatially unique. Regular and measurable patterns define the historical record of storm tracks. For example, storms near the island of Grenada rarely move up the East Coast; instead, they normally impact some portion of the Gulf Coast. Therefore, should residents of North Carolina pay attention to a storm near Grenada? This dissertation does not attempt to answer that question; instead, it provides a historical perspective allowing people in North Carolina to assess the climatological risk of impact given a current position. More information in the hands of the general public allows better decisions to be made regarding individual and public safety. In today's society, access to information is demanded by the public.

APPENDIX A

CONVERSION TABLES

Table A.1 Wind speed conversions.

Knots	M/S	MPH
30.0	15.4	34.5
35.0	18.0	40.3
65.0	33.4	74.8
100.0	51.4	115.0
130.0	66.9	149.5
150.0	77.2	172.5

Table A.2 Distance conversions.

Statute Miles	Nautical Miles
1.0	1.2
5.0	5.8
10.0	11.5
50.0	57.5
100.0	115.0
1000.0	1150.0

Table A.3 Temperature conversions.

°F	°C
-10.0	-23.3
0.0	-17.8
32.0	0.0
50.0	10.0
80.0	26.7
100.0	37.8

APPENDIX B

LANDFALL TABULATION BY STATE OR REGION

Table B.1 Count of number of hexagons in each landfall probability category for the entire United States.

Probability (%)	No. of Hexagons
90 - 100	271
80 - 90	56
70 - 80	50
60 -70	70
50 - 60	188
40 - 50	204
30 - 40	253
20 - 30	278
10 - 20	255
2 - 10	196
< 2	1554

Table B.2 Count of number of hexagons in each landfall probability category for Texas.

Probability (%)	No. of Hexagons
90 - 100	24
80 - 90	5
70 - 80	7
60 -70	7
50 - 60	14
40 - 50	12
30 - 40	42
20 - 30	121
10 - 20	229
2 - 10	303
< 2	2611

Table B.3 Count of number of hexagons in each landfall probability category for Louisiana.

Probability (%)	No. of Hexagons
90 - 100	21
80 - 90	5
70 - 80	4
60 -70	5
50 - 60	9
40 - 50	13
30 - 40	35
20 - 30	111
10 - 20	247
2 - 10	421
< 2	2504

Table B.4 Count of number of hexagons in each landfall probability category for Mississippi, Alabama, and the Florida panhandle.

Probability (%)	No. of Hexagons
90 - 100	37
80 - 90	8
70 - 80	2
60 -70	7
50 - 60	36
40 - 50	39
30 - 40	69
20 - 30	261
10 - 20	402
2 - 10	292
< 2	2222

Table B.5 Count of number of hexagons in each landfall probability category for the Florida peninsula.

Probability (%)	No. of Hexagons
90 - 100	34
80 - 90	7
70 - 80	10
60 -70	14
50 - 60	27
40 - 50	43
30 - 40	108
20 - 30	215
10 - 20	404
2 - 10	354
< 2	2159

Table B.6 Count of number of hexagons in each landfall probability category for Georgia.

Probability (%)	No. of Hexagons
90 - 100	5
80 - 90	2
70 - 80	4
60 -70	3
50 - 60	11
40 - 50	7
30 - 40	21
20 - 30	70
10 - 20	279
2 - 10	555
< 2	2418

Table B.7 Count of number of hexagons in each landfall probability category for South Carolina.

Probability (%)	No. of Hexagons
90 - 100	9
80 - 90	2
70 - 80	4
60 -70	3
50 - 60	12
40 - 50	11
30 - 40	34
20 - 30	161
10 - 20	453
2 - 10	505
< 2	2181

Table B.8 Count of number of hexagons in each landfall probability category for North Carolina.

Probability (%)	No. of Hexagons
90 - 100	13
80 - 90	3
70 - 80	5
60 -70	4
50 - 60	9
40 - 50	19
30 - 40	58
20 - 30	206
10 - 20	511
2 - 10	485
< 2	2062

Table B.9 Count of number of hexagons in each landfall probability category for Virginia, Maryland, and Delaware.

Probability (%)	No. of Hexagons
90 - 100	20
80 - 90	2
70 - 80	6
60 -70	6
50 - 60	12
40 - 50	6
30 - 40	39
20 - 30	224
10 - 20	472
2 - 10	505
< 2	2083

Table B.10 Count of number of hexagons in each landfall probability category for New Jersey.

Probability (%)	No. of Hexagons
90 - 100	6
80 - 90	2
70 - 80	3
60 -70	1
50 - 60	7
40 - 50	6
30 - 40	9
20 - 30	20
10 - 20	183
2 - 10	569
< 2	2569

Table B.11 Count of number of hexagons in each landfall probability category for New York.

Probability (%)	No. of Hexagons
90 - 100	6
80 - 90	4
70 - 80	2
60 -70	2
50 - 60	6
40 - 50	4
30 - 40	17
20 - 30	41
10 - 20	219
2 - 10	562
< 2	2512

Table B.12 Count of number of hexagons in each landfall probability category for Connecticut, Rhode Island, Massachusetts, and New Hampshire.

Probability (%)	No. of Hexagons
90 - 100	24
80 - 90	6
70 - 80	3
60 -70	10
50 - 60	11
40 - 50	6
30 - 40	25
20 - 30	96
10 - 20	413
2 - 10	610
< 2	2171

Table B.13 Count of number of hexagons in each landfall probability category for Maine.

Probability (%)	No. of Hexagons
90 - 100	14
80 - 90	5
70 - 80	2
60 -70	6
50 - 60	12
40 - 50	15
30 - 40	14
20 - 30	40
10 - 20	241
2 - 10	675
< 2	2351

APPENDIX C

SUPPLEMENTAL PROBABILITY MAPS

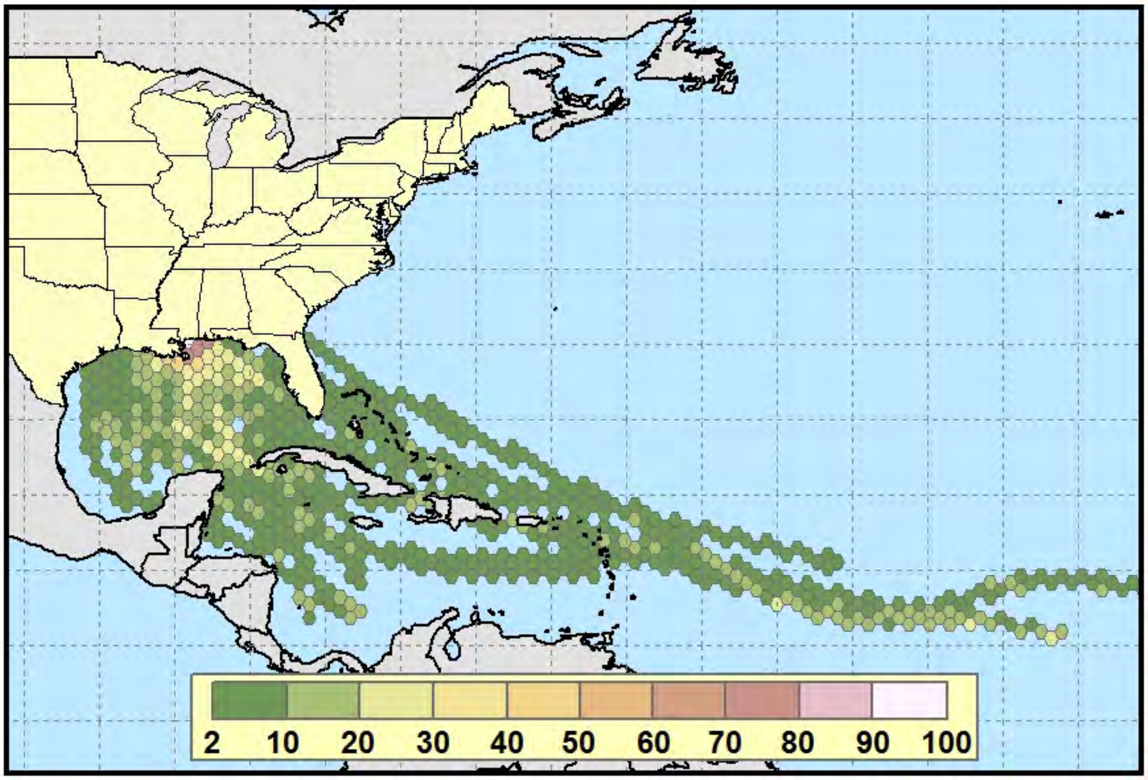

Figure C.1 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Mississippi or coming within 30 nautical miles of Mississippi (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 93.

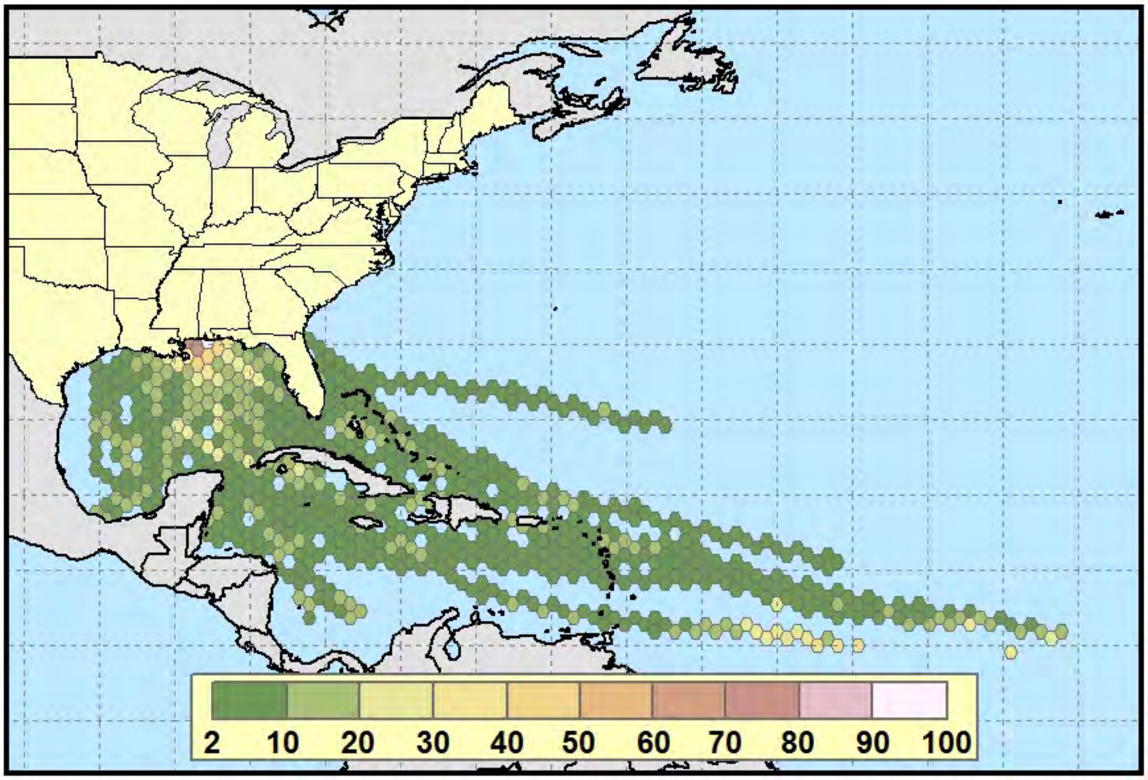

Figure C.2 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Alabama or coming within 30 nautical miles of Alabama (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 102.

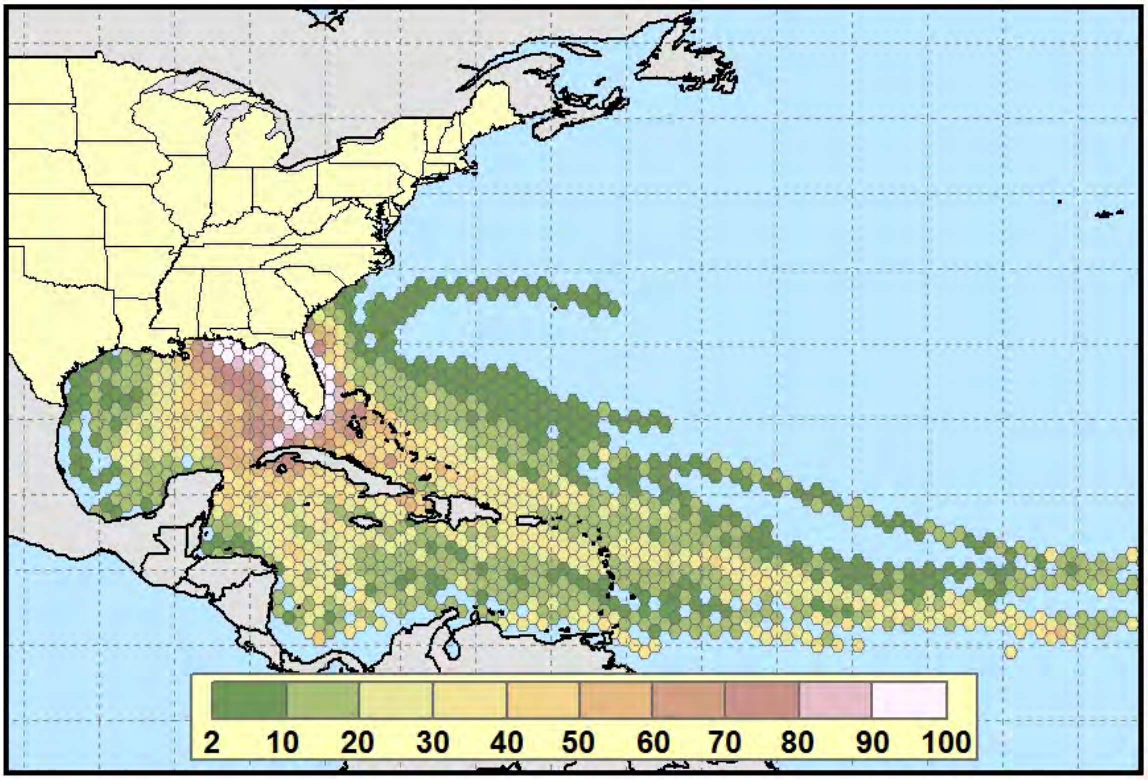

Figure C.3 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Florida or coming within 30 nautical miles of Florida (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 245.

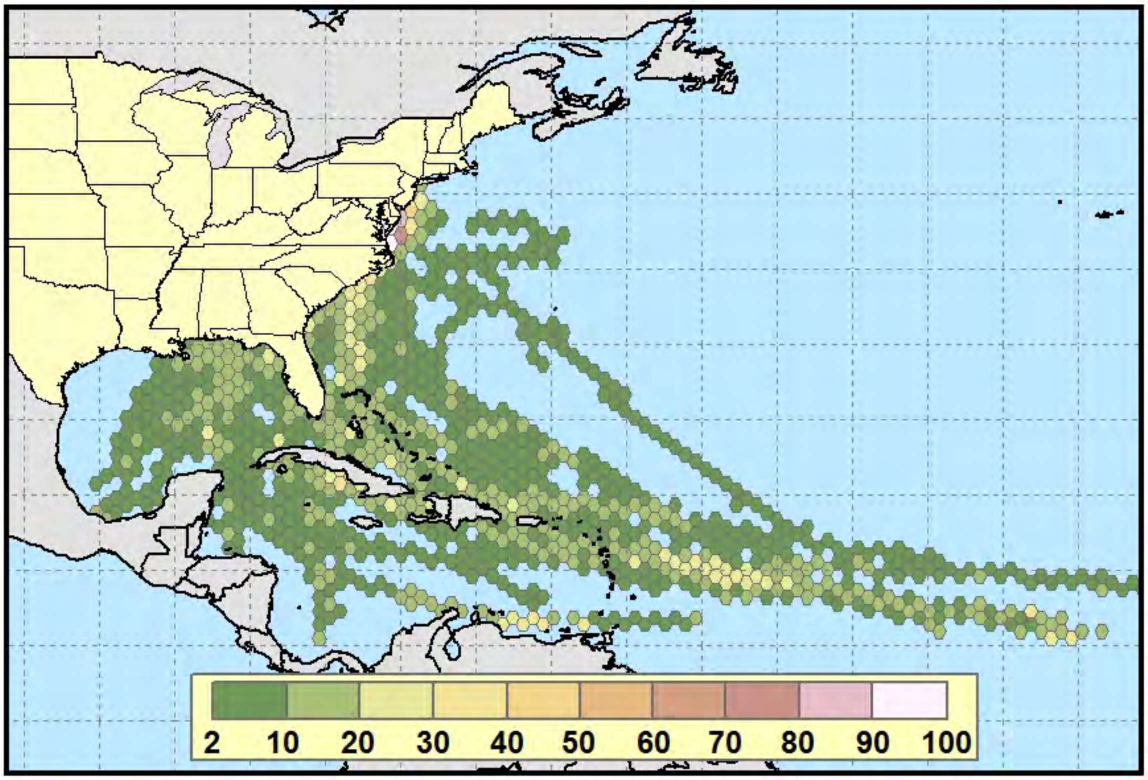

Figure C.4 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Virginia or coming within 30 nautical miles of Virginia (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 89.

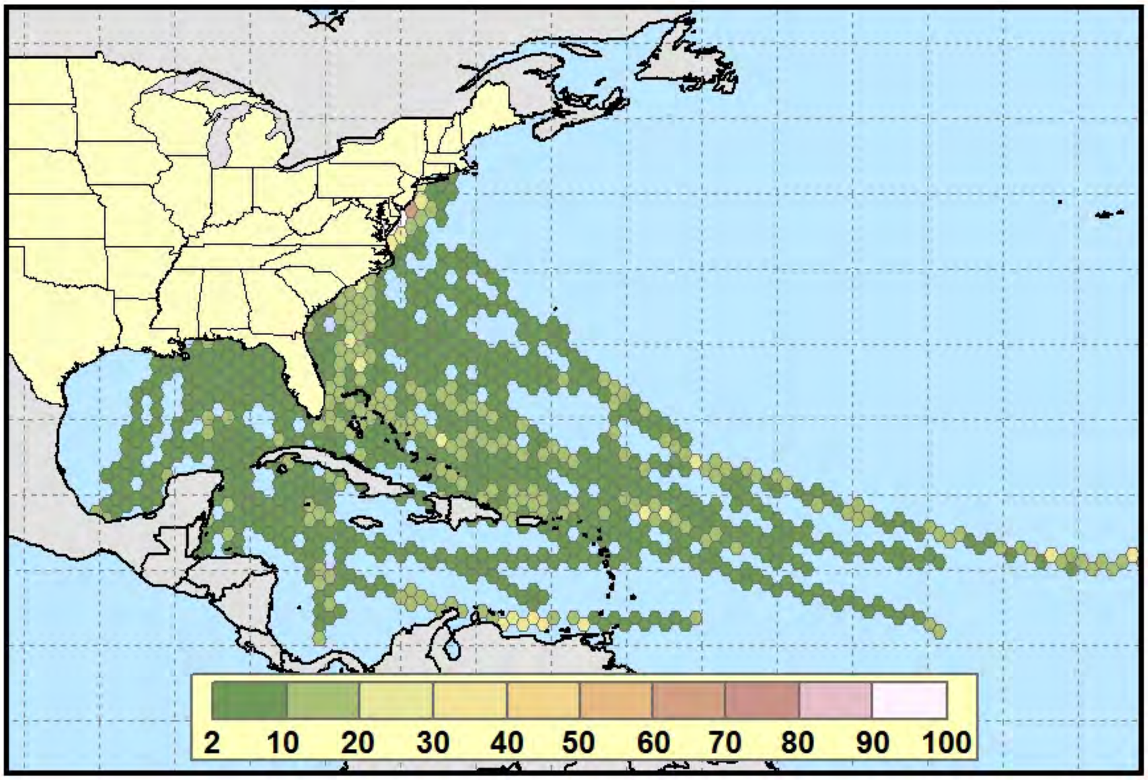

Figure C.5 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Maryland or coming within 30 nautical miles of Maryland (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 57.

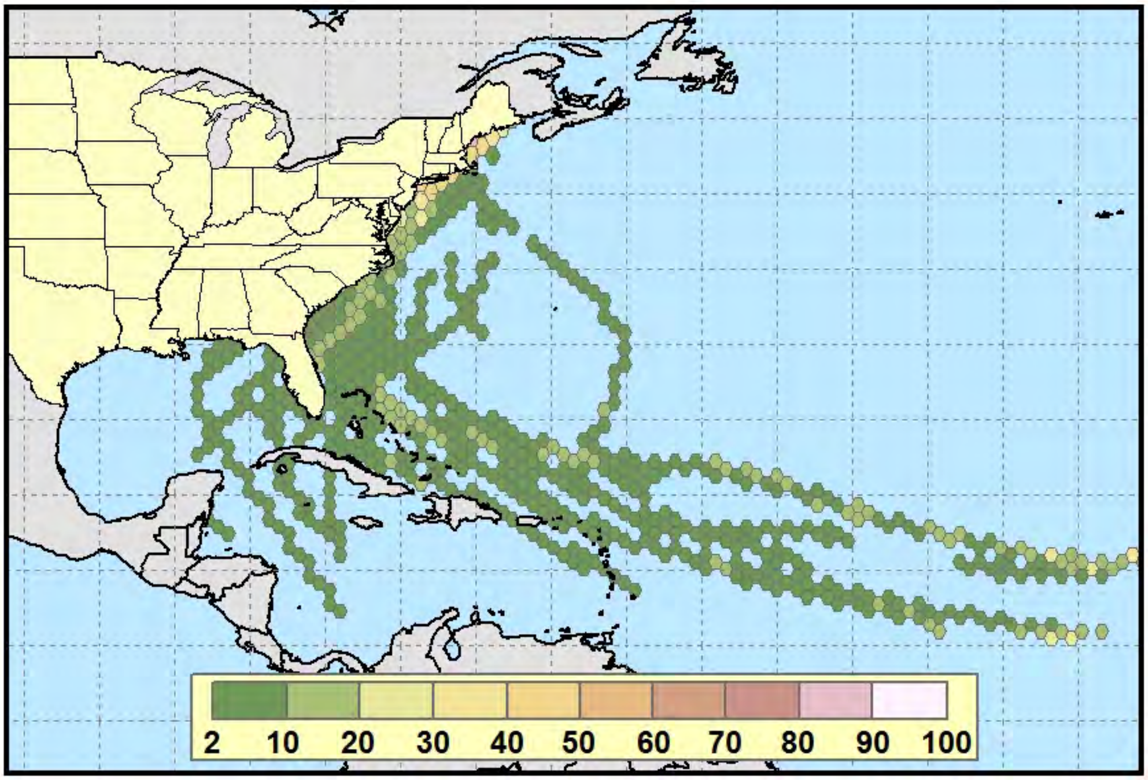

Figure C.6 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Delaware or coming within 30 nautical miles of Delaware (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 38.

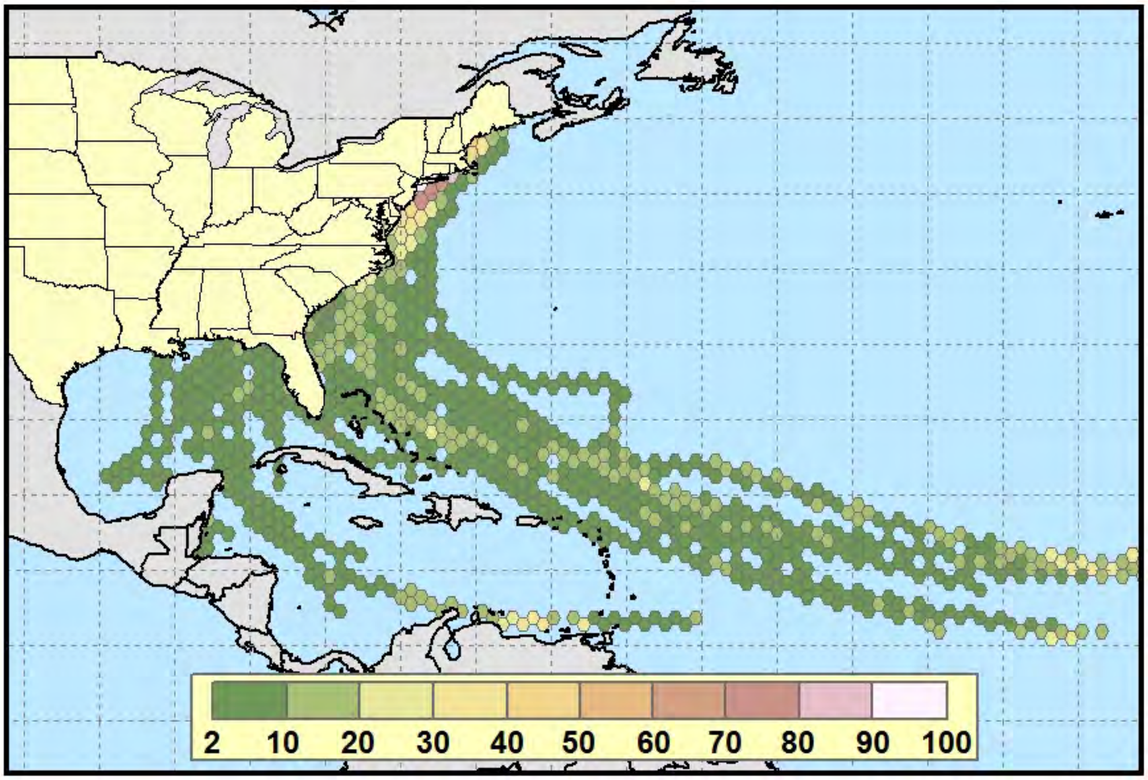

Figure C.7 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Connecticut or coming within 30 nautical miles of Connecticut (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 40.

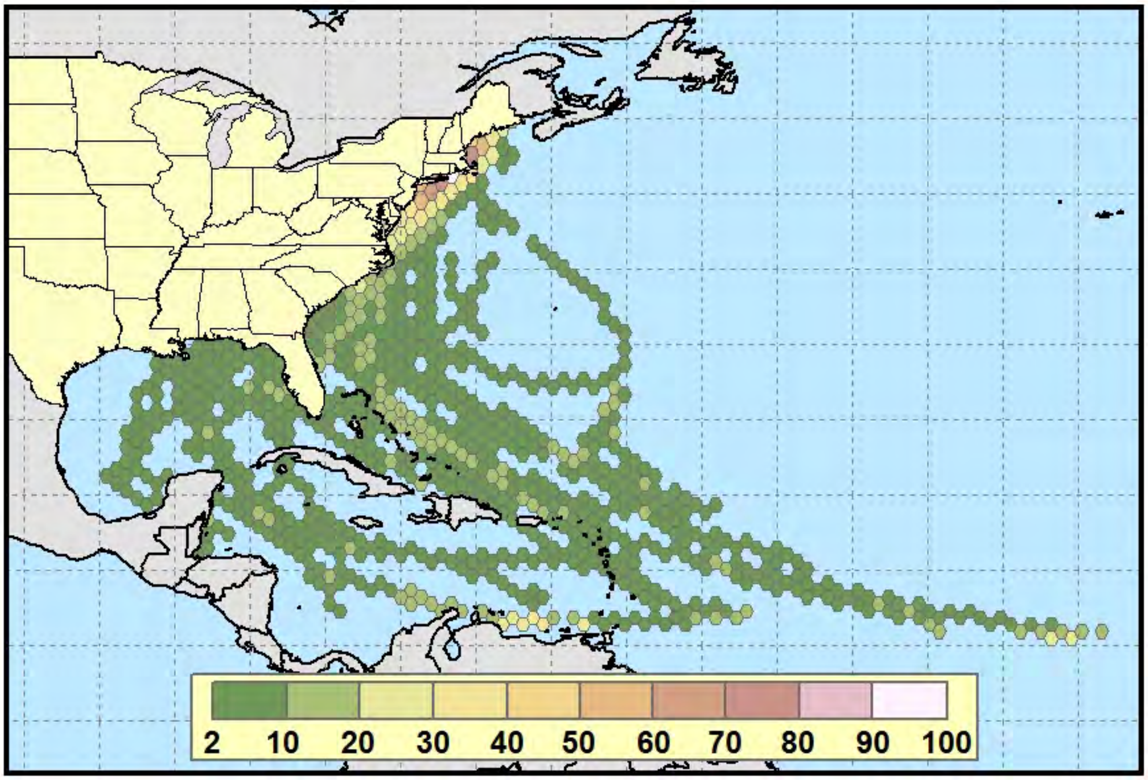

Figure C.8 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Rhode Island or coming within 30 nautical miles of Rhode Island (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 37.

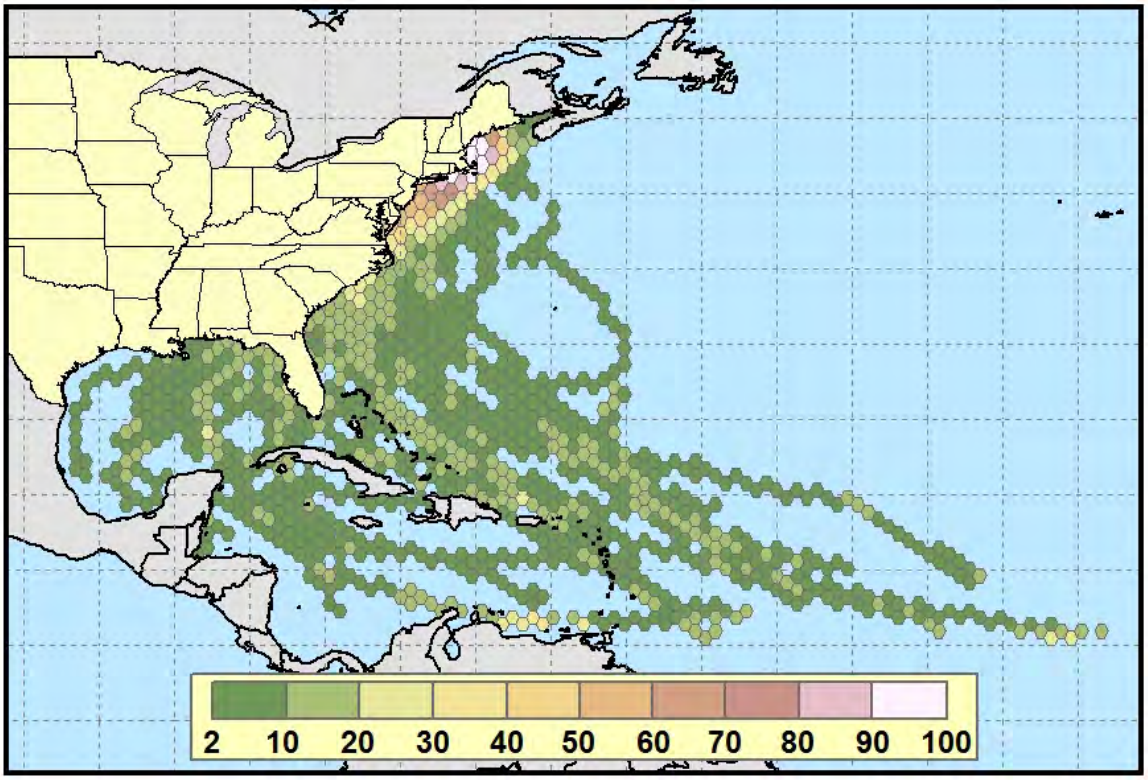

Figure C.9 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking Massachusetts or coming within 30 nautical miles of Massachusetts (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 69.

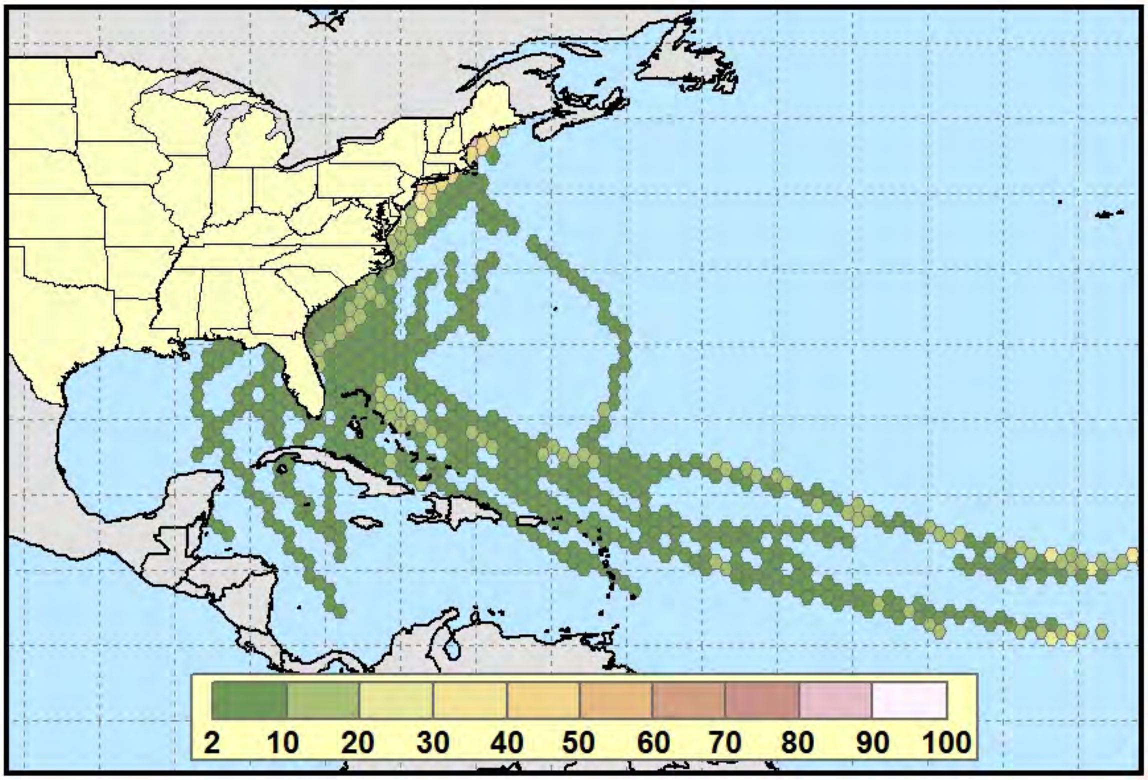

Figure C.10 Probability for the North Atlantic Basin of storms passing through equal area hexagons eventually striking New Hampshire or coming within 30 nautical miles of New Hampshire (measured as a percentage). Period of record is 1851-2004. Number of affecting storms is 31.

APPENDIX D

ADDITIONAL MAPS

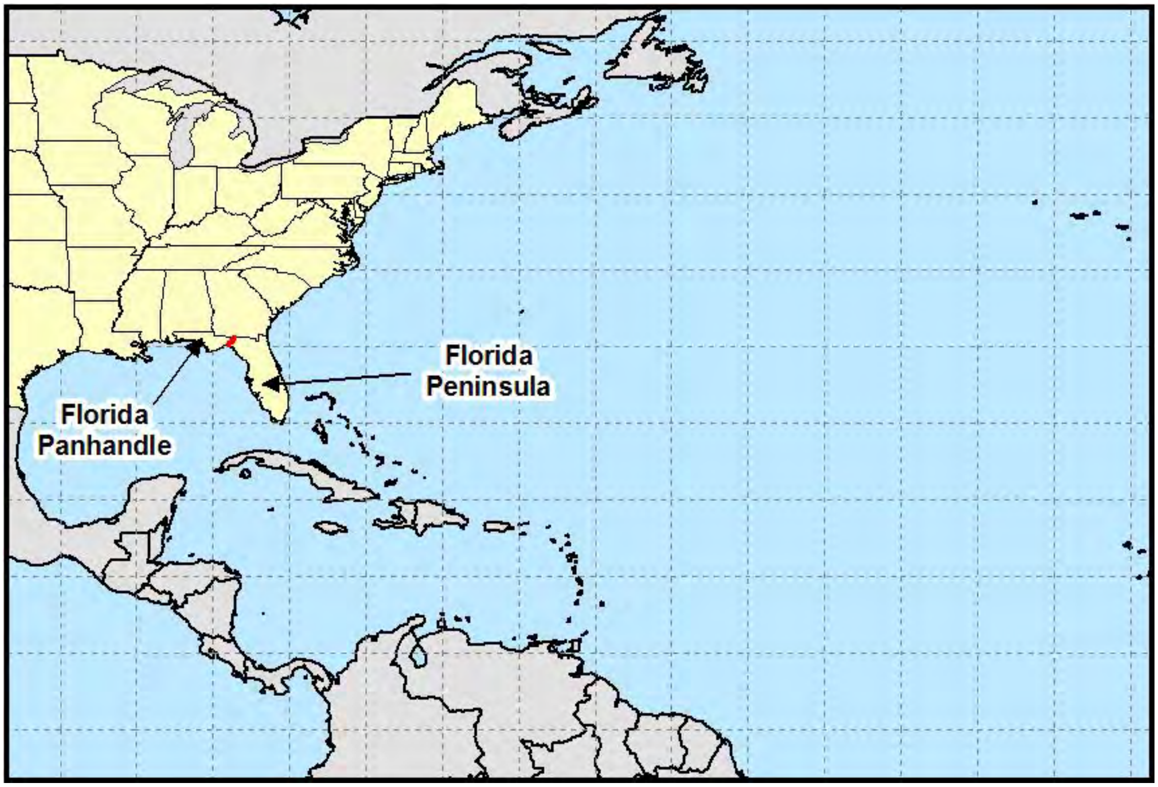

Figure D.1 Delineation between the Florida panhandle and the Florida peninsula. The red line represents the eastern boundary of Jefferson County, Florida.

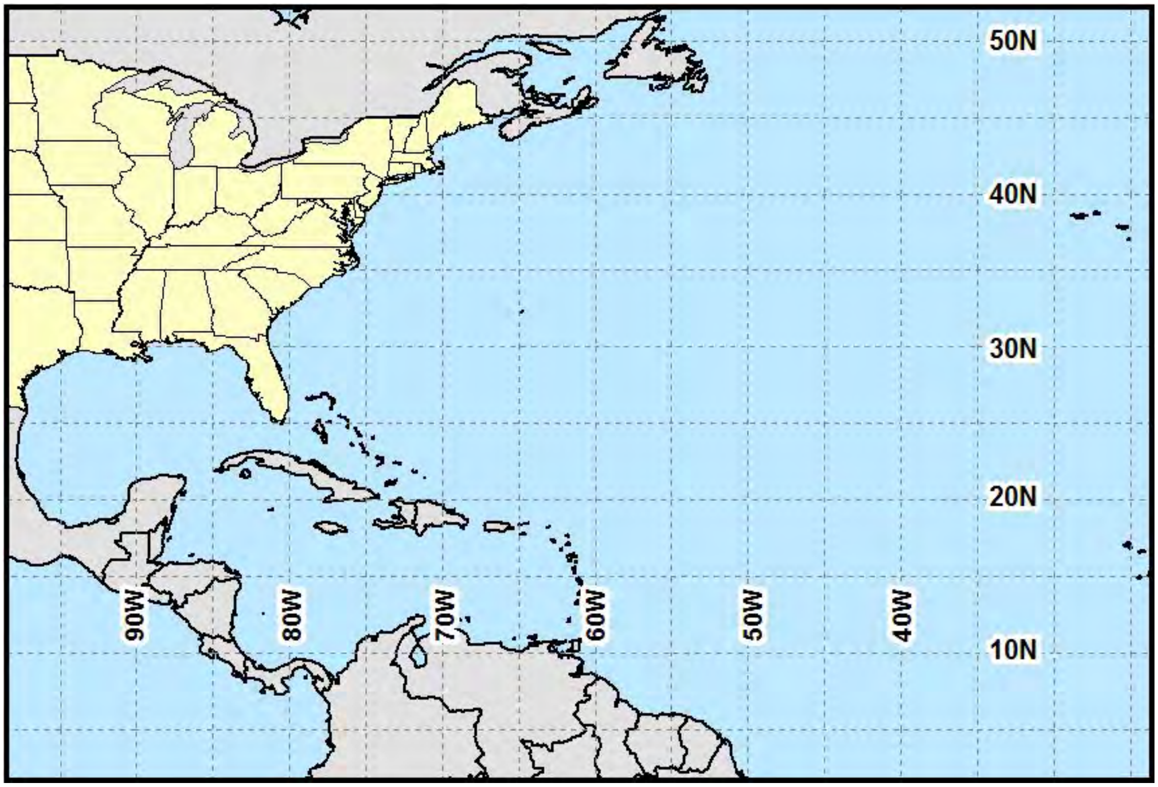

Figure D.2 The Atlantic Basin with lines of latitude and longitude labeled for reference.

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VITA

Brian Brettschneider was born in Houston, Texas, in 1971, the son of Ralph and Cynthia Brettschneider. After graduating from high school in 1988, Brian attended several colleges before enrolling at Texas State University-San Marcos in 1991. He graduated with a Bachelor's of Science degree in Geography and Planning in December 1994 with a concentration in Cartography and Photogrammetry and a minor in Mathematics. Brian immediately enrolled in the graduate program at Texas State and earned a Master's of Applied Geography with an emphasis in Cartography and Geographic Information Systems (GIS) in August 1997. After a brief trial as a doctoral student, Brian began working as an Environmental Scientist for an environmental consulting firm in Houston, Texas. In 2004, he returned to Texas State to complete his doctoral studies and graduated in December 2006 with a PhD in Environmental Geography.

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