AN ANALYSIS OF HURRICANE SEASONS IN THE PRE-HURDAT ERA (1751-1850)

A THESIS
SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE
MASTER OF SCIENCE

BY

STEVEN A. LAVOIE
DR. JILL COLEMAN, ADVISOR
BALL STATE UNIVERSITY
JULY 2011
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BALL STATE UNIVERSITY
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JULY 2011
I would like to thank the dedicated educators in the geography department at Ball State University for providing me with new skills to further my career and assist me in reach my personal career goals. I would also like to thank the former and current members of my committee, Dr. Matthew Wilson, Dr. Kevin Turcotte, Dr. Petra Zimmermann, and advisor Dr. Jill Coleman for making me work out my initial methodological issues and helping me redirect my thesis. I am grateful to my entire committee for pointing out the flaws that I refused to accept in the proposal stage of my thesis thus avoiding major issues in the future. Most importantly, I would like to acknowledge my thesis advisor Dr. Jill Coleman who, over the course of just two years, also served as my mentor, my professor, and my employer. I hope to make you all proud one day and yes, I still aspire to become director of the National Hurricane Center.
ABSTRACT

THESIS: An Analysis of Hurricane Seasons in the Pre-HURDAT Era (1751-1850)

STUDENT: Steven A. LaVoie

DEGREE: Master of Science

COLLEGE: Science and Humanities

DATE: July, 2011

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An extensive database of the tracks of tropical cyclones in the North Atlantic Ocean since 1851 is known as the North Atlantic Hurricane Database (HURDAT). While this database is valuable to public and private agencies, many of the deadliest hurricanes on record occurred prior to 1851. This study will address the research problem of the availability of historical information and the feasibility of collecting data and producing historical tropical cyclone tracks. This thesis describes a methodology for identifying tropical cyclones that existed during the one hundred year period from 1751-1850 referred to as the “pre-HURDAT era” in this study. Uncovering historical tropical cyclone tracks are important for researchers seeking long term patterns in the climate record. This study is a synthesis of all readily available historical data which can be used to identify the tracks of documented tropical cyclones that occurred during the pre-HURDAT era. To emphasize the applicability of historical hurricane tracks, a study comparing landfall patterns of landfalling east coast hurricanes was also done. These tracks were analyzed using historical chronologies, ship data, and other “regional literature”.
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Chapter I: Introduction

An extensive database comprised of the tracks of tropical cyclones in the North Atlantic Ocean after 1850 is known as the North Atlantic Hurricane Database or HURDAT. While this database is a valuable tool to public and private agencies alike, some of the deadliest hurricanes on record in the North Atlantic basin occurred prior to the beginning of the HURDAT record. Table 1.1 lists the 30 deadliest known hurricanes of all time in the Atlantic basin which shows that 40% of the 30 deadliest and 30% of the 10 deadliest Atlantic hurricanes on record occurred prior to the commencement of the HURDAT database. Among these is the deadliest known Atlantic hurricane, the Great Hurricane of 1780, which killed an estimated 22,000 people and was one of eight known tropical cyclones during that season (Ludlum, 1963).

Table 1.1: The 30 deadliest recorded Atlantic hurricanes. Hurricanes that occurred prior to 1851 are highlighted. Table populated with information found at http://www.nhc.noaa.gov/pastdeadlyapp1.shtml?

<table>
<thead>
<tr>
<th>Rank</th>
<th>Year</th>
<th>Name</th>
<th>Deaths</th>
<th>Rank</th>
<th>Year</th>
<th>Name</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1780</td>
<td>The Great Hurricane</td>
<td>22,000+</td>
<td>16</td>
<td>1831</td>
<td>Great Barbados Hur.</td>
<td>2,500</td>
</tr>
<tr>
<td>2</td>
<td>1997</td>
<td>Mitch</td>
<td>19,325</td>
<td>17</td>
<td>1931</td>
<td>Unnamed</td>
<td>2,500</td>
</tr>
<tr>
<td>3</td>
<td>1900</td>
<td>Galveston Hurricane</td>
<td>12,000</td>
<td>18</td>
<td>1935</td>
<td>Unnamed</td>
<td>2,150+</td>
</tr>
<tr>
<td>4</td>
<td>1974</td>
<td>Fifi</td>
<td>10,000</td>
<td>19</td>
<td>1979</td>
<td>David</td>
<td>2,068+</td>
</tr>
<tr>
<td>5</td>
<td>1930</td>
<td>Hurricane San Zeon</td>
<td>8,000</td>
<td>19</td>
<td>1781</td>
<td>Unnamed</td>
<td>2,000+</td>
</tr>
<tr>
<td>6</td>
<td>1963</td>
<td>Flora</td>
<td>8,000</td>
<td>20</td>
<td>1893</td>
<td>Sea Islands Hurricane</td>
<td>2,000+</td>
</tr>
<tr>
<td>7</td>
<td>1776</td>
<td>Pointe a Pitre Bay Hur.</td>
<td>6,000+</td>
<td>21</td>
<td>1780</td>
<td>Solano’s Hurricane</td>
<td>2,000</td>
</tr>
<tr>
<td>8</td>
<td>1775</td>
<td>Newfoundland Hurricane</td>
<td>4,000</td>
<td>22</td>
<td>1870</td>
<td>Hurricane San Marcos</td>
<td>2,000</td>
</tr>
<tr>
<td>9</td>
<td>1899</td>
<td>Hurricane San Ciriaco</td>
<td>3,433+</td>
<td>23</td>
<td>1870</td>
<td>Hurricane Caminada Hurr.</td>
<td>2,000</td>
</tr>
<tr>
<td>10</td>
<td>1928</td>
<td>Okeechobee Hurricane</td>
<td>3,411+</td>
<td>24</td>
<td>1893</td>
<td>Unnamed</td>
<td>2,000</td>
</tr>
<tr>
<td>11</td>
<td>1932</td>
<td>Unnamed</td>
<td>3,107+</td>
<td>25</td>
<td>1666</td>
<td>Unnamed</td>
<td>2,000</td>
</tr>
<tr>
<td>12</td>
<td>2004</td>
<td>Jeanne</td>
<td>3,025</td>
<td>26</td>
<td>2005</td>
<td>Katrina</td>
<td>1,836</td>
</tr>
<tr>
<td>13</td>
<td>1813</td>
<td>Unnamed</td>
<td>3,000+</td>
<td>27</td>
<td>2005</td>
<td>Stan</td>
<td>1,628</td>
</tr>
<tr>
<td>14</td>
<td>1934</td>
<td>Unnamed</td>
<td>3,000+</td>
<td>28</td>
<td>1767</td>
<td>Unnamed</td>
<td>1,600</td>
</tr>
<tr>
<td>15</td>
<td>1791</td>
<td>Hurricane Las Puentes</td>
<td>3,000</td>
<td>29</td>
<td>1909</td>
<td>Unnamed</td>
<td>1,500</td>
</tr>
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</table>
Many researchers have stressed the importance of identifying historical tropical cyclones to understand long term trends in tropical cyclone activity. One of the most heated debates related to this topic is the link between tropical cyclones and anthropogenic global warming (AGW) with one researcher stating that “An emerging focus is how the frequency…has changed over time and whether any changes could be linked to anthropogenic global warming…long-term ‘trends’ in tropical cyclone frequency are primarily manifestations of increased monitoring capabilities and likely not related to any real change in the climate in which they develop.” (Landsea, 2007). While quantitative meteorological data decreases in availability during earlier time periods, information derived from historical archives such as ship logs and newspaper accounts can be used to estimate the track of tropical cyclones. The primary objective of this study is to develop a methodology for incorporating all available historical data in order to analyze the tracks of tropical cyclones occurring during the pre-HURDAT era.

The one hundred year period from 1751-1850, known as the “Pre-HURDAT Era” in this study, is the time period of focus. While many previous researchers including Chenoweth (2006), Ludlum (1963), and Tannehill (1938) have published listings of tropical cyclones that occurred in the Atlantic prior to 1851, there has not been a comprehensive study illustrating basin-wide tropical cyclone tracks in the period prior to the HURDAT database. Those who have analyzed tracks have typically focused on a sub-region of the Atlantic as opposed to studying the basin as a whole. In order to show the practicality of doing such an analysis, research comparing landfall patterns along the east coast of the United States for two decades of the nineteenth century (before HURDAT) and the twentieth century (using HURDAT data) was completed. The tracks of the pre-HURDAT tropical cyclones are estimated using historical chronologies, ship data, and other archival information and entered into ArcGIS. By comparing similar tracks from the
modern era, it may be possible to reconstruct the synoptic patterns for hurricanes during the pre-HURDAT era despite the lack of data. This is just one of many possible applications for pre-HURDAT historical data.

The record of past tropical cyclones provides an important approach to evaluate the hurricane hazard. Historical chronologies are one source of tropical cyclone information before the start of HURDAT in 1851. The most recently published chronology, Chenoweth (2006), contains an archive of 383 tropical cyclones occurring between 1700 and 1855. This study describes a method for taking historical archives and chronologies like the one found in Chenoweth (2006) and utilizing them to estimate tracks of historical tropical cyclones. In order to do this, an event is assigned a series of geographic coordinates based on available archival data. The sensitivity of the methodology to the accuracy and quality of data and incorporation of new data is also addressed. This study shows that historical archives can provide useful information about pre-HURDAT era cyclones which may help climatologists better understand long-term variations in tropical cyclone activity. These observed variations in tropical cyclone activity are compared to three different teleconnections to see if any relationship exists.
Chapter II: Literature Review

This study aims to develop a methodology to reconstruct tropical cyclone tracks using historical documents. This type of study falls under a subdiscipline of climatology known as paleotempestology. Studies from various fields have used a Geographic Information System (GIS) as a tool to display historical data. Similar to the Historical Hurricane Information Tool, this study also uses a GIS to display information, in this case the reconstructed historical tropical cyclone tracks.

2.1 Paleotempestology

The study of past tropical cyclone activity by means of geological proxies and/or historical documentary records is known as paleotempestology. This scientific discipline has become prominent over the course of the last decade partially in response to the recent increase in tropical cyclone count and intensity in the North Atlantic basin witnessed since 1995. The field has also developed due to the socioeconomic impacts of tropical cyclones particularly along vulnerable coastal regions. During the twenty-five years prior to the start of the most recent increase in hurricane activity, major (Category 3, 4, or 5) hurricanes were less frequent than in previous decades. However, property losses from the hurricanes that did make landfall in the United States increased during this period due to development in damage prone areas (NOAA Paleoclimatology Program, 2000). Despite several devastating hurricane landfalls in the United States since 2000, coastal population continues to increase and an analysis of hurricane risk can have significant implications on many socioeconomic fields including tourism development and
Prior to the emergence of the discipline of paleotempestology, historians and researchers studied the impacts of hurricanes in the northeastern United States for a variety of reasons. Since the coast of New England was among the first regions colonized by Europeans, the region has some of the longest historical records in the western hemisphere. Perley (1891) utilizes the historical records of New England to compile a history of natural phenomenon from 1620-1890. He did this by researching old newspaper articles, shipping logs, and diaries of the period. While specific meteorological details, such as wind speed and barometric pressure, were less frequent, Perley’s descriptions of tropical cyclones provide information which can contribute to event reconstruction. Tropical cyclones are a major factor dictating the structure, function, and dynamics of the ecosystems of many coastal forests but their role can only be understood by assessing impacts over an extended period of time (Boose et al., 2001). This was done for the New England states using a combination of historical research and computer modeling starting in 1620 and estimating wind speeds using the Fujita Scale where the return periods for tree damage resulting from F1 and F2 wind speeds were calculated.

2.1.1 Geological Proxies

In addition to utilizing historical documents, paleotempestological studies have also been done using sedimentary records, tree rings, and other geological proxies. When an ocean storm or tsunami produces a surge, coastal sediments are brought inland up to several miles away from the ocean (Donnelly et al., 2004). These sediments are preserved in lakes and marshes located near the ocean and are collected by scientists to estimate the dates of significant surge events generated by from tropical cyclones, strong winter cyclones, or tsunamis depending on the
region of interest. The method of using coastal sediment records was originally used to identify tsunami events but the markers associated with storm surge are very similar if not identical. Several studies have been done along the coast of the Gulf of Mexico (Liu, 1998 and Liu and Fearn, 2000) and several states along the east coast of the United States. Following several surge events associated with a series of powerful ocean storms, restoration efforts began along the coast of Long Island, New York. During this process Dr. Nicholas Coch and his team discovered hundreds of artifacts dating back to the 1890s. Further analysis of meteorological and archeological data indicated that an island existed south of Rockaway until a powerful hurricane in 1893 made landfall wiping out the barrier island and its inhabitants (Coch and Jarvinen, 2000).

Previous sediment overwash studies have aided in confirming the existence of major hurricanes along the east coast of the United States during the pre-HURDAT era. One such study looked at sedimentary records in Rhode Island and determined that at least seven major hurricanes made landfall in New England in the last 700 years (Donnelly et al., 2001). Five of the hurricanes occurred prior to the start of HURDAT (1635, 1638, and 1815) while two of these five occurred prior to European settlement. A study in New Jersey (Donnelly et al., 2004) showed that in addition to uncovering overwash deposits for the notable twentieth century east coast hurricanes, older deposits were identifiable. Two of these deposits were from hurricane strikes in 1821 and 1788 and reinforce the intensity of these hurricanes (Category 2-3) when they impacted the northeastern United States. Studies of North Atlantic paleohurricane activity have also been done in the Caribbean in both the Antilles (Donnelly and Woodruff, 2007) and Central America (McCloskey and Keller, 2009).

Tree ring analysis is another useful tool for identification of pre-HURDAT tropical cyclones. Miller et al. (2006) present a 220-year record of oxygen isotope values in longleaf pine
tree rings. They link anomalously low isotope values in the latewood portion of the ring with tropical cyclones that impacted the southeastern United States. One tree ring sample in Valdosta, Georgia shows evidence of a hurricane around 1780 and has been linked with Solano’s Hurricane. This hurricane caused approximately 2,000 deaths in the eastern Gulf of Mexico but the track of the cyclone beyond this region was not known. This study supports the hypothesis that the hurricane made landfall along the northwestern Florida coast and passed near Valdosta on its way across the southeastern United States and out to sea. This track extension is also suggested in Chenoweth (2006).

2.1.2 Historical Documents

Another aspect of paleotempestological research focuses on the examination of historical documents to reconstruct the tracks of tropical cyclones. When a strong tropical storm or hurricane makes landfall in a populated area, its impacts are typically recorded and can range from a description of damage to detailed hourly observations. For accounts of tropical cyclones on land, most accounts are in the form of newspapers, some of which simply reprint a story featured in another newspaper in the afflicted area. This introduces the possibility of misunderstood information and occasionally tropical cyclones are referred on days where no such storm occurred. There are some cases where two sources will have conflicting information on the date a tropical cyclone made landfall. Sometimes the date is off by as much as a year and is due to a typographical error where an erroneous hurricane was added to the list and is actually a double entry.

Errors in the dating of tropical cyclones found in newspapers can be corrected by analyzing government records and shipping logs. By 1751, the start of the pre-HURDAT era,
most of the western hemisphere was claimed by a colonial power. When a hurricane devastates a colony, accounts of the event are relayed to the European power that controls the region (England, France, Spain, the Netherlands, or Portugal). These accounts are recorded in newspapers and colonial documents and are stored in the archival collections of Europe. Countries that gained independence during the pre-HURDAT era will also have similar archives in their libraries but a majority of government and colonial documents are currently not available in a digitized format.

The logs of various ships provide our only information while tropical cyclones are over the open ocean. During the pre-HURDAT era, these logs were for merchant ships transporting goods across the Atlantic as well as warships which roamed the Atlantic on several occasions during the period. The frequency of ship reports on a yearly basis varied and is based on the amount of trade between countries and the level of conflict, if any. A majority of the ship reports used in this study came from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) but the amount of reports during the pre-HURDAT era is very limited. However, other ship reports are available but are not currently in an easily assessable format.

### 2.1.3 Chronologies

Historians have used archival data to comprise comprehensive chronologies of Atlantic tropical cyclones prior to the start of HURDAT, each with a different approach. A chronology consists of a listing of events which includes dates and locations of impact. Pre-HURDAT tropical cyclones from 1751-1800 were identified using six of these chronologies. The foundation for most of the chronologies written over the last century stems from a paper written by Andrés Poey (1855) who used available data such as shipping logs and newspaper accounts to
catalog 400 cyclones that formed in the Atlantic basin dating back to the explorations of Columbus with a focus on the Caribbean region. Not possessing the modern knowledge of the differences in tropical cyclone structure, Poey included in his catalog cyclones that were certainly non-tropical in nature forming outside of the traditional bounds of the hurricane season and/or in an unusual location such as the far north Atlantic. Poey also did not attempt to link landfalls in different regions of the basin that were clearly associated with the same hurricane resulting in multiple entries. Some of these errors would be unintentionally included in future chronological listings.

Perhaps the most widely used chronology referenced today is that one constructed by Tannehill (1938), which is an update of the Poey chronology and builds upon previous tropical cyclone track and/or impact reconstructions. Though more qualitative than quantitative, Tannehill (1938) does include the tracks of some of the most noteworthy tropical cyclones of the period such Racer’s Storm (1837), the Antigua-Charleston Hurricane (1804), and The Great Hurricane of 1780. The primary issue with the chronology of Tannehill and his predecessors is the existence of erroneous or unreferenced data which is pointed out in Ludlum (1963), Millás (1968), and Chenoweth (2006).

While some historians would do little to prove the existence of the tropical cyclones in the Poey chronology, others such as Millás (1968) and Ludlum (1963) reexamined these tropical cyclones on a case by case basis and provided additional evidence supporting their decision to accept or reject a particular entry as a valid tropical cyclone. Millás (1968) examined the Poey database from 1492 until 1800 for the entire Atlantic basin with a focus on the Caribbean. The Historical Hurricane Information Tool (HHIT), a GIS database with a focus on the United States (Bossak and Elsner, 2003), is utilized as the sixth primary source for the second half of the pre-
HURDAT period (1800-1850). Each entry of the Millás chronology is analyzed and the author cites not only previous historians but includes summaries some of historical documents he used to prove or refute the existence of an entry. Ludlum (1963) examined early American (1492-1870) tropical cyclones and his chronology contains details for landfalls along the Atlantic and Gulf of Mexico coasts. Unlike Millás (1968), the Ludlum chronology does not include any rejected entries and focuses on providing all available information on known tropical cyclones. Both Ludlum (1963) and Millás (1968) contain numerous references to entries found in Poey (1855) and especially Tannehill (1938).

The other chronologies used in this study are Chenoweth (2006) and Dunn and Miller (1960). The Dunn and Miller chronology divides the United States into regions and lists significant tropical cyclones for each area as opposed to one chronological listing. The intent of the Chenoweth chronology was to remove all inconsistencies and inaccuracies found in previous chronologies. The author references over a dozen chronologies and regional studies dating back to the early eighteenth century to analyze what he believes is a fully corrected listing of 198 tropical cyclones from 1700-1855. Although Chenoweth provides a chronology that is better quality than its predecessors, it is not free of error. An example of one probable error in Chenoweth (2006) is examined in detail in Chapter 3.

2.1.4 Regional Studies

Researchers have collected newspaper articles, diaries, ship logs, and other archival documents in an attempt to identify historical tropical cyclone landfalls in the decades prior to the start of our modern record for various regions of the United States. For his 1891 publication,
Sidney Perley collected newspapers, diaries, and other relevant documents from the northeastern United States and pieced together the impacts of tropical cyclones throughout the region. In his book on early American hurricanes, historian David Ludlum (1963) used a variety of regional literature to describe the role of tropical cyclones in early American history. This included many descriptions of New England landfalls including the Great September Gale of 1815, the most powerful tropical cyclone to strike New England in the nineteenth century (Ludlum, 1963, 1988). Jay Barnes published two regional studies for the states of North Carolina (Barnes, 2001) and Florida (Barnes, 2007) respectively. Sandrik and Landsea (2003) conducted a study for Georgia and northeastern Florida while Hairr (2008) published another study for North Carolina. Finally, three unpublished studies were done by David Roth for Virginia (2007), Louisiana (2010a), and Texas (2010b) which includes information on a total of 85 pre-HURDAT tropical cyclones.

The results of regional studies are primarily qualitative descriptions of weather phenomena and societal impacts that typically lack quantitative information. While quantitative information such as measurements of wind speed and barometric pressure would be preferred as opposed to descriptions of the event, this type of data becomes increasingly less frequent as we move backwards in time. Despite this shortcoming, regional histories are useful and can be used as a tool for determining the return periods of hurricanes to a specific region. They can also be used to estimate the strength of the winds at a location (i.e. Boose 2001, Bossak 2003, and Chenoweth 2006).
2.1.5 Individual Historical Tropical Cyclone Reconstructions

The process of taking historical information to reconstruct the tracks of individual pre-HURDAT hurricanes has been done by a variety of authors. This process was utilized for one tropical cyclone in 1680 that formed near the Cape Verde Islands, impacted the Lesser Antilles, and struck Europe as a powerful extratropical cyclone (Wheeler et al. 2009). One of the many mysteries of pre-HURDAT tropical cyclones surrounded the “Independence Hurricane” which made landfall in North Carolina on September 2nd, 1775 killing 163 people. It was originally believed that this hurricane later made landfall in Newfoundland on September 12th killing approximately 4,000 people. This unlikely scenario was explored in Rappaport and Ruffman (1999) when the tracks of two individual hurricanes were reconstructed. Tony Williams (2008) wrote a book on the historic 1775 hurricane that struck North Carolina and roared through the colonies and made the same conclusion which was that the Newfoundland Hurricane was a separate entity from that one that struck the colonies at the dawning of the American Revolutionary War. A track reconstruction was done for another hurricane that occurred at the commencement of a war. The 1812 Great Louisiana Hurricane was reconstructed as a major hurricane that took a “worst case scenario” track for the city of New Orleans (Mock et al., 2010).

Historical reconstructions of hurricanes have also been done in areas that do not see the impacts of tropical cyclones. When Hurricane Vince made landfall in Spain as a tropical depression in October 2005, it was stated that it was the first tropical cyclone to make landfall in Europe. However, it was not noted that this statement was for the modern record which goes back to 1851. It was uncovered that a tropical storm made landfall in Spain in October 1842 which appears to have had a very similar genesis and track to Vince (Vaquero et al., 2008). The state of California is another location that is not acquainted with the impacts of hurricanes due to
the cold California current which weakens any poleward moving tropical cyclone. However, the track of an 1858 hurricane that directly impacted San Diego was reconstructed. While it is believed the hurricane did not make landfall in California, a reoccurrence of this event would “threaten lives and causes hundreds of millions of dollars in damage” (Chenoweth and Landsea, 2004).

2.1.6 The Modern Record

Researchers have questioned the accuracy and comprehensiveness of HURDAT, the official record of tropical cyclones in the North Atlantic basin which covers the period 1851-2010. This is due in part to the digitization of data and its recent availability to the general public. Researchers now have access to key data that was largely inaccessible to historians because it was stored within libraries and other archives that required international travel to access the information. In light of this new data, a team of researchers led by Dr. Landsea has been doing a reanalysis of every cyclone in HURDAT, a process outlined in Landsea et al. (2004). In order to update information found in HURDAT, a research team must acquire sufficient evidence to prove that the information found within the database of a certain entry is erroneous. For example, if a weak hurricane was recorded in the central Atlantic but there is no evidence of 64kt (hurricane force) winds, it will be downgraded to a tropical storm in the reanalysis. The primary motivation behind the HURDAT reanalysis was the work of Fernandez-Partagas and Diaz (1995a; 1995b; 1996a; 1996b; 1997; 1999) whose diligent analysis of historical archives from 1851-1910 allowed the HURDAT database to be extended backwards in time to include the late nineteenth century. Members of the reanalysis team used the information found in the publications of Fernandez-Partagas and Diaz as a foundation for estimating the track
and intensity of tropical cyclones during the 1851-1910 period using typical methods of estimation including the pressure-wind relationship, an inverse relationship between sea level pressure and wind speed at a location. Over 5000 additions and alterations have been made to HURDAT prior to 1911 (Landsea et al., 2004) and the HURDAT reanalysis is complete for the years 1851-1930.

2.1.7 Tropical Cyclone Frequency and Teleconnections

When looking at the modern record, we see a gradual increase in the frequency of tropical cyclone activity in the North Atlantic that is marked by alternating periods of increased and decreased activity. To further explore these long term trends and link them to the pre-HURDAT era, the frequency of tropical cyclones are compared with three teleconnections. These teleconnections are the Atlantic Multi-decadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO). All three of these teleconnections can have significant impacts on the frequency and intensity of tropical cyclones in the North Atlantic.

The AMO is an observed pattern in Sea Surface Temperatures (SSTs) in the North Atlantic Ocean which has been linked to changes in the frequency of Atlantic tropical cyclones where a positive AMO values favor enhanced tropical cyclone activity (Mann and Emanuel, 2006). The PDO is a long lived pattern in SSTs over the Northern Pacific Ocean which has been linked to the El Niño Southern Oscillation (ENSO) and inversely to Atlantic tropical cyclone activity (Newman et al., 2003). Finally, the NAO is a “seesaw” pattern in the intensity of the Bermuda-Azores High and the Icelandic Low which in turn has a significant role in the strength
of westerly winds and storm tracks in the North Atlantic. A positive NAO results in an increased pressure gradient between the Bermuda-Azores High and the Icelandic Low which generally increase the intensity of the trade winds. This not only alters the tracks of tropical cyclones but more importantly lower the SSTs of the region due to increased ocean to atmosphere heat transfer (Elsner and Jagger, 2009).

2.2 GIS and Historical Studies

Various studies in the past have utilized a GIS to display historical data. A historical GIS study takes archival data derived from historical maps, ship reports, newspaper accounts, and other documents and displays the results. In this study, the results are historical hurricane tracks but this is not always the case. In a GIS, data can be represented using points, lines, and shapes and can be used to show both spatial and temporal patterns in the data. For example, one historical GIS study used patterns in eighteenth century land grant records to analyze settlement patterns in parts of North Carolina (Dobbs, 2009).

Many countries have been using historical GIS for analysis of historical events. In Ireland, spatial patterns were analyzed during the Irish Potato Famine of the late nineteenth century (Ell and Gregory, 2005). In the United States, an initiative has been made to preserve the conditions of historical battle sites. A total of 98 battlegrounds of the American Civil War were analyzed and land use maps were produced to see how the land has changed since the war (Bellas, 1994). Many countries have a national historical GIS database including the United States, Great Britain, Germany, Russia, and China. Over time, it may be possible to develop
regional historical GIS databases using data from various countries and for events on a global scale such as famines, disease outbreaks, and wars.

Historical GIS has also been a useful tool for meteorological studies. A study was done to analyze the impacts of 85 hurricanes that have impacted Puerto Rico since the first date of European settlement in 1508. For the 43 hurricanes since 1851, a simple GIS based meteorological model known as HURRECON was used to reconstruct specific impacts (Boose and Foster, 2006). A methodology for using spatial hazard data (both historical and modern) to estimate the impacts of various natural calamities including tropical cyclones for insurance purposes is outlined in Dempster et al. (2008). Government agencies such as the NOAA and FEMA have historical GIS data available online. For example, historical wind information for the state of Minnesota has been compiled in order to display the most ideal location for wind turbines (Minnesota Dept. of Commerce, 2006). The HURDAT database has been transformed into an online GIS called Historical Hurricane Tracks which can be used to see the tracks of historical tropical cyclones (1851-2010) for any location in the United States.

### 2.3 Using GIS to Reconstruct Early 19th Century Hurricanes

A historical GIS-based study which identified tropical cyclone tracks in the pre-HURDAT era was done by Brian Bossak and James Elsner (Bossak, 2003 and Bossak and Elsner, 2003). This study was done as a dissertation and consists of the actual paper (Bossak, 2003) and the Historical Hurricane Information Tool (Bossak and Elsner, 2003) which is a database of significant tropical cyclones that impacted the United States from 1800-1850. The primary goal of this project was to make historical data more accessible to hurricane researchers,
emergency managers, and climatologists. Each track file also includes other files with callouts containing verbatim accounts of the event. This digital format was chosen so that the tracks could easily be altered when additional information about a specific tropical cyclone is acquired. The authors used historical publications, chiefly Ludlum (1963), to estimate the geographical coordinates for these tropical cyclones and were displayed using ArcGIS.

While the database contains valuable information and is one of the six primary sources used for the latter half of the pre-HURDAT era (1800-1850), there are some limitations to the database. The authors almost exclusively used Ludlum (1963) to reconstruct their tracks limiting both the amount of data and not incorporating possible errors in the assumptions made by Ludlum. Ludlum (1963) also lacks many quantitative details which can be obtained directly from other historical documents such as newspaper accounts and especially shipping logs. Another disadvantage of the database is that the tracks are exclusive to the waters near the United States and do not extend outside this region. In order to be of use to climatologists looking for long term trends in the frequency of tropical cyclones in the North Atlantic, tracks should be reconstructed for the entire basin whenever possible. A final caveat is that this study does not make any attempts to make connections with the modern record, which is one of the potential uses of tropical cyclone data prior to 1851. This study is different from that one done by Bossak and Elsner (2003) because it aims to show that long term trends in tropical cyclone frequency can be made and that it is possible to estimate the tracks of pre-HURDAT tropical cyclones to regions beyond the United States.
Chapter III: Data and Methodology

The primary objective of this study is to develop a methodology for identifying and reconstructing historical tropical cyclone tracks not currently in the HURDAT database. Prior to the start of HURDAT in 1851, a myriad of sources are needed to reconstruct hurricane frequencies and tracks, such as newspaper accounts, shipping logs, diaries, descriptive summaries, and chronologies. Taking these mostly qualitative, and occasionally conflicting or inaccurate, accounts of hurricanes and extracting information to develop a series of geographic coordinates is a significant challenge of historical hurricane database construction. The hurricane track reconstructions presented here are a result of identifying potential sources of quantitative and qualitative data, analyzing the historical archives, creating a tabular database for further data analysis, and finally creating the spatial dataset, including ArcGIS shapefiles. This method advances chronological studies such as Chenoweth (2006) by taking a list of geographical locations impacted by hurricane and presenting the resultant tracks in a visual medium. This is an improvement over a similar GIS study done by Bossak and Elsner (2003) which used only one primary source (Ludlum 1963) and limited hurricane tracks to the vicinity of the United States.

The utility of extending the hurricane database prior to 1850 is then shown by identifying the preferred tracks of recorded landfalling hurricanes during two decades of the pre-HURDAT era, the 1820s and 1830s, and comparing them with two decades of the modern record, the 1950s and 1960s. Table 3.1 identifies the primary datasets used to identify hurricane tracks during these two study periods and their respective number of landfalls in eastern North America. As Table 3.1 illustrates, information on hurricane frequencies in the pre-HURDAT era can have significant
variability depending on the data source. The six primary sources indicate that the 1820s and 1830s had anywhere between 13 and 20 East Coast hurricane landfalls. Each primary source constructs their listing of tropical cyclones differently. Three sources (Chenoweth 2006, Tannehill 1938, and Poey 1855) simply list the dates of the event and the names of locations impacted while Millás (1968) and Ludlum (1963) provide evidence either supporting or refuting an event and the final primary source (Dunn and Miller 1960) breaks landfalls into different regions but again only lists dates and places. These two eras are studied because of the similar level of hurricane activity and due to the fact that we can attempt to use twentieth century reanalysis data to reconstruct the synoptic environment of nineteenth century tropical cyclones. The primary sources used in this study are reviewed in depth in the next section.

Table 3.1: A comparison of the 1950-69 and 1820-39 North Atlantic tropical cyclone frequencies along the eastern United States coastline listed by primary data source.

<table>
<thead>
<tr>
<th>Source</th>
<th>Study Period</th>
<th>East Coast Landfalls</th>
</tr>
</thead>
<tbody>
<tr>
<td>HURDAT</td>
<td>1950-1969</td>
<td>18</td>
</tr>
<tr>
<td>Chenoweth (2006)</td>
<td>1820-1839</td>
<td>19</td>
</tr>
<tr>
<td>HHIT (2003)</td>
<td>1820-1839</td>
<td>18</td>
</tr>
<tr>
<td>Ludlum (1964)</td>
<td>1820-1839</td>
<td>20</td>
</tr>
<tr>
<td>Dunn and Miller (1960)</td>
<td>1820-1839</td>
<td>13</td>
</tr>
<tr>
<td>Tannehill (1938)</td>
<td>1820-1839</td>
<td>18</td>
</tr>
<tr>
<td>Poey (1855)</td>
<td>1820-1839</td>
<td>14</td>
</tr>
</tbody>
</table>
3.1 HURDAT

For the twentieth century, track and landfall information from the HURDAT database is used as it is considered the most comprehensive and accurate database available. The database was created in the 1960s in support of the Apollo space program to help provide statistical tropical cyclone track forecasting guidance (Jarvinen et al. 1984). The original database contained six hourly “best track” track and intensity information for all known tropical cyclones starting in 1886 and was later maintained by the National Hurricane Center. Researchers later used the database for a variety of projects including establishing building codes, risk assessment, and intensity predictions. It soon became apparent that the database was not suited for such tasks and needed to be expanded in order to meet these demands.

For the past decade, the HURDAT database has been going through an extensive reanalysis. The reanalysis, led by Dr. Landsea, attempts to correct all errors found within HURDAT in order to produce the most accurate database available. This reanalysis included the addition of thirty-five years of tropical cyclone data to HURDAT, the addition or removal of tropical cyclones, and an update of notable individual tropical cyclones such as Hurricane Andrew (1992) which was upgraded to a Category 5 hurricane at landfall in Florida. Thus far the reanalysis has been completed for all tropical cyclones during the 1851-1930 period and will continue through the modern era. Dr. Landsea has stated that the HURDAT database should be extended earlier as far as possible but that such work would not be done by the reanalysis team until the current revision was completed. Despite likely containing several errors for the 1950s and 1960s, the HURDAT database was chosen because it is the most straightforward and readily available hurricane database in existence.
3.2 Pre-HURDAT Data Sources

In order to conduct a temporal study of tropical cyclone activity prior to the start of HURDAT, data must first be extracted from historical archives containing mainly descriptive information and nominal level data. Quantitative measurements such as temperature and barometric pressure were very sparse in the pre-HURDAT era and were limited to larger population centers and some ships. Table 3.2 lists the information provided for the numerous sources used in the pre-HURDAT analysis including the data and author, the period of record, and the number of tropical cyclone entries. Although some of these references are contemporaries of one another, each source provides a different type of information that may or may not be duplicated (i.e. summaries of accounts of the event) and aids in determining the tracks of tropical cyclones; however, these references do not include sources for individual entries, only summations. The six chronologies contain a listing of tropical cyclones, locations impacted, and the dates of impact which can provide a rough outline of the track while near land. Two of the authors, Millás (1968) and Ludlum (1963), gathered historical documents and provide descriptive information for each entry. In addition to the chronologies, several regional studies have been done and provide critical information on tropical cyclones in New England, North Carolina, Georgia, and Florida. Finally, the Historical Hurricane Information Tool (HHIT) provides information and tracks for American hurricanes in the first half of the nineteenth century. The HHIT and the six chronologies are considered the primary sources for the analysis and are explained in depth in the following sections.
**Table 3.2:** Information for the various sources used in the pre-HURDAT analysis.

<table>
<thead>
<tr>
<th>Source Name</th>
<th>Type</th>
<th>Author(s)</th>
<th>Record</th>
<th>Relevant Entries</th>
<th>Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Millás (1968)</td>
<td>Book/Chronology</td>
<td>Jose Millás</td>
<td>1492-1800</td>
<td>136</td>
<td>Caribbean</td>
</tr>
<tr>
<td>Ludlum (1963)</td>
<td>Book/Chronology</td>
<td>David Ludlum</td>
<td>1492-1870</td>
<td>76</td>
<td>United States</td>
</tr>
<tr>
<td>Dunn &amp; Miller (1960)</td>
<td>Book/Chronology</td>
<td>Gordon Dunn Banner Miller</td>
<td>1559-1958</td>
<td>101</td>
<td>United States</td>
</tr>
<tr>
<td>Tannehill (1938)</td>
<td>Book/Chronology</td>
<td>Ivan Tannehill</td>
<td>1492-1855</td>
<td>327</td>
<td>N. Atlantic Basin</td>
</tr>
<tr>
<td>Perley (1891)</td>
<td>Book</td>
<td>Sydney Perley</td>
<td>1635-1890</td>
<td>8</td>
<td>New England</td>
</tr>
<tr>
<td>Poey (1855)</td>
<td>Article/Chronology</td>
<td>Andrés Poey</td>
<td>1492-1855</td>
<td>296</td>
<td>N. Atlantic Basin</td>
</tr>
</tbody>
</table>

Not listed in Table 3.2 are the sources utilized for the analysis of individual pre-HURDAT tropical cyclones. In populated cities of the North Atlantic, newspapers would summarize accounts of hurricanes, both firsthand from their city as well as stories from sailors visiting their ports. Shipping logs provided one of the few available sources of both wind speed and direction. These ship reports can help locate the center of circulation and are especially valuable over water. In addition to newspapers accounts and shipping logs, a variety of personal documents such as diaries, letters, and colonial correspondence have survived or have been
reproduced. These personal accounts generally provide a summary of the damage the hurricane wrought and may help in determining if the tropical cyclone was a true hurricane. For example, if there is evidence that the hurricane may have been extratropical at the time of landfall (i.e. rapid temperature changes and/or wind behavior associated with frontal boundaries), it may be removed.

\section*{3.2.1 The Poey Chronology}

Several attempts to populate a listing of all cyclonic storms in the Caribbean were made in the early nineteenth century. However, the best known and most comprehensive chronology in the North Atlantic was created by Andrés Poey (1855), a native of Cuba. With a focus on the Caribbean where data was most readily available to him, Poey created a list of cyclonic storms since the voyages of Columbus with the first entry occurring in early 1493. To build his list of cyclonic storms, he used previous chronologies that were geared towards a specific island as a base for his listing and added available historical documents, newspaper accounts, and shipping logs. The primary caveat of using the Poey chronology is that it is a listing of all cyclonic storms meaning that the listing, including the first entry, provided details for both tropical and non-tropical cyclones. There were many cases in which Poey listed two or more entries for what was clearly one continuous cyclone. Despite being published over 150 years ago and being riddled with these inaccuracies, the Poey chronology was reviewed because it serves as the foundation for chronologies published after 1855 and provides some details not found in the other primary sources. Of the 296 entries Poey listed from 1751-1850, 219 were accepted into the master list. Entries were primarily rejected because they were either duplicates entries or non-tropical
entities. For the cases in which Poey listed two or more entries for one continuous cyclone
information was merged before being entered into the master database.

3.2.2 *Hurricanes: Tannehill (1938)*

The first considerable update of the original Poey listing occurred in the 1930s. Ivan
Tannehill published the first edition of his book *Hurricanes* in 1938 and included an update of
the Poey chronology. Tannehill had access to American data sources not available to Poey and
was able to update some of Poey’s entries and added others. Poey’s chronology included many
cyclonic storms that he believed were clearly non-tropical in nature (i.e. Storms that impacted the
far North Atlantic and Europe) and Tannehill removed these entries in addition to almost every
entry occurring between December and May, months outside of the traditional bounds of
hurricane season. Despite making several amendments to the Poey chronology, Tannehill did not
attempt to combine entries that were clearly the same cyclone (i.e. a strike to Barbados followed
by a strike to Hispaniola two days later) and as a result these errors are transferred from the 1855
chronology to the 1938 listing. Tannehill did, however, estimate the tracks of 29 tropical
cyclones of the era including the three deadly hurricanes of October 1780 (Figure 3.1). These
tracks were incorporated into the master list and the final tracks were modified if needed. Of the
327 entries Tannehill listed from 1751-1850, 305 were accepted into the master list. The reasons
for rejecting entries were the same as with the Poey chronology.
Figure 3.1: The tracks of three October hurricanes in 1780 (Figure 70 in Tannehill 1938).

3.2.3 Atlantic Hurricanes: Dunn and Miller (1960)

The 1960s was a decade of renewed interest in historical tropical cyclones likely spurred from a spike in hurricane activity during the previous decade which was due in part to the invention of weather radar and satellite technology. During this decade, three different chronologies were published with the first appearing in the book Atlantic Hurricanes by Dunn and Miller which was published in 1960. Like Tannehill (1938), this was a book on tropical cyclones which included a chronology. This chronology was specifically for the United States, one of the earliest exclusively American chronologies available. Since Poey (1855) focused on the Caribbean, it was not the primary source for this chronology but did provide some information to the authors to supplement the other sources that were utilized. Unlike previous listings, the Dunn and Miller chronology split the American coastline into six groups of states. Since events were broken down by region, there were several cases where the same tropical
cyclone would appear as two or more individual entries. Of the 101 entries Dunn and Miller listed from 1751-1850, 93 were accepted into the master list. The eight cases that were removed were hurricanes that existed in more than one region.

3.2.4 Early American Hurricanes: Ludlum (1963)

Three years following Atlantic Hurricanes Ludlum published a book that exclusively focused on historical hurricanes. The book Early American Hurricanes provides detailed accounts of tropical storms and hurricanes that impacted the American coastline and included reproductions of historical accounts. Unlike previous authors, Ludlum reviewed the documents from a meteorological perspective and estimated the location and movement of some of the more prominent tropical cyclones of the early American period. Ludlum viewed each storm on a case-by-case basis in an attempt to prove or disprove its existence as a tropical cyclone while previous authors simply included any reference to a “hurricane” in their listing. This book is the primary source for the HHIT produced by Bossak and Elsner forty years later. Also found in some of the individual entries are shorter descriptions of other tropical cyclones that did not impact the United States but were significant enough in the eyes of Ludlum to be mentioned. Since Ludlum included many other tropical cyclones within each entry, the number of entries accepted in the master list increased from 75 entries printed in Ludlum (1963) for the period to 113 individual tropical cyclone entries.
3.2.5 *Hurricanes of the Caribbean*: Millás (1968)

The final chronology of the 1960s was created by Millás and published in 1968. The book published in 1968 by Millás is essentially the Caribbean equivalent to Ludlum (1963) and cites both Tannehill (1938) and Poey (1855) as his primary sources. Millás updates the Poey chronology and reviews each entry in depth providing evidence that supports or refutes the existence of each entry. For example, the author rejects four of the seven 1752 hurricanes because he could not find any evidence of their existence in the regional histories of various Caribbean islands. Unlike previous chronologies, the Millás listing ends in 1800 but provides documentation for dozens of accounts in the 1751-1800 period. Of the 136 entries Millás listed from 1751-1800, 124 were accepted into the master list. Rejected entries were not included if Millás rejected the entry and there was no evidence available to refute his claim.

3.2.6 *Historical Hurricane Information Tool (HHIT)*: Bossak and Elsner (2003)

The remaining primary sources were both published in the previous decade and use many of the previous authors as a foundation for their studies. The first of these sources is a GIS database which provides not only track data but supporting evidence for tropical cyclones of the early nineteenth century. The HHIT is available to the public and uses historical archives, knowledge of the behavior and structure of tropical cyclones, and GIS to document the impacts of 91 individual tropical cyclones that impacted the American coastline between 1800 and 1850. This listing includes five additional entries not found in any of the other primary sources but appeared in secondary sources. The authors cite their primary source as Ludlum (1963) but incorporates approximately a dozen other sources. Bossak and Elsner (2003) is the study that
most closely resembles the methodology outlined in this paper due to its GIS component and analysis of historical hurricane tracks.

3.2.7 The Chenoweth Chronology (2006)

The final and most recent chronology was published in 2006 by Chenoweth. While the author cites Poey (1855) as his primary source, he uses many other chronologies as a foundation for his study. Advancements in technology such as the digitizing of historical documents have provided hurricane researchers with new data sources which were either unavailable and/or located in Europe. Utilizing these new data sources, Chenoweth revises the chronologies of both Poey (1855) and Millás (1968) rejecting cases he could not find sufficient data to support. While the Chenoweth chronology is one of the most accurate and comprehensive listing of historical tropical cyclones available, there are several errors which have been revealed in this study. One of the most notable errors is with the third tropical cyclone of the 1788 hurricane season. Chenoweth treats this hurricane, known as Hurricane San Rouge in Puerto Rico and the western New England hurricane in Ludlum (1963), as two separate entities when evidence supports one continuous track. This entry will serve as an example in later sections of the chapter.

3.3 Potential Caveats

Despite the wide range of resources available, each source has caveats that must be considered when extracting data from them. While HURDAT is a comprehensive database, it is undergoing a revision as it is likely that up to 3.2 tropical cyclones were missed in the North
Atlantic each year prior to 1966 (Landsea, 2007), the commencement of continuous satellite monitoring of the north Atlantic basin. The HHIT provides users with track information for recorded tropical cyclones that threatened the United States between 1800 and 1850. However, the creators of the database used many of the same sources as this study to prepare tracks and they do not directly address the possible errors of each source. An additional disadvantage to using the HHIT is that the tracks do not extend beyond the vicinity of the United States. In fact, many of the sources listed in Tables 3.1 and 3.2 focus on a specific state or region of interest as opposed to the entire North Atlantic basin.

The primary difficulty with utilizing chronologies is that most authors use previous chronologies as a foundation for their studies and as a result, some incorrect data is transferred into the updated chronology. As mentioned earlier, the primary source Tannehill used in his 1938 chronology was the article by Poey (1855) and Tannehill left many of the errors found in that article in his chronology. The disadvantage of many newspaper accounts is that many of them contain secondhand reproductions from other newspapers or sources which can result in a miscommunication of details. While shipping logs are our most accurate source for hurricane tracks at sea, anemometers were generally unavailable and wind speed was estimated using the Beaufort scale, which at sea is based mainly on wave height. Prior to the creation of the Beaufort scale in the early nineteenth century, wind was simple described as “hurricane force” and not directly measured or compared.

For this study each caveat is addressed on an individual basis as opposed to looking for caveats throughout each source. While the HHIT does display tracks of early nineteenth century hurricanes, the tracks are not taken verbatim if other evidence is available to alter the track. For example, the track of the 1821 Norfolk and Long Island Hurricane presented in HHIT shows an
initial landfall near Cape Hatteras while this study estimates landfall further to the west along the mainland of North Carolina. In addition, it is apparent that the hurricane passed through New Jersey as opposed to remaining just offshore as depicted in the HHIT. Though some of the primary sources are regional studies, they are combined together since we have many instances of a hurricane in the Caribbean later impacting the United States. In cases where it is known that an entry contains errors which have been passed from author to author, the entry is modified or removed before being incorporated in the master list.

3.4. Analysis of Historical Archives

While many of the primary sources provide important details, they are derived from a summary of the original accounts of tropical cyclones. Because of this it is best to utilize the original accounts whenever possible. There has been an effort over the past decade to digitize historical documents and make them available online. For this study, all newspaper reports came from newspaperarchive.com which contains many of the original documents that historians like Millás and Ludlum featured in their publications. Figure 3.2 depicts selections from four London newspapers regarding a hurricane that appears to have impacted several Caribbean islands as well as the northeastern United States in August 1788. This is the hurricane that Chenoweth believes was two separate entities. Many of the countries of the western hemisphere were controlled by European powers for some portion of the pre-HURDAT era and correspondence from the colonies arrived in Europe periodically and was then relayed in newspapers. The difference in time between the event and the publishing of accounts in London newspapers shows how slow news traveled during the pre-HURDAT era. The lack of a quick communication
network explains, in part, why many communities were unprepared when hurricanes struck during this time period.

Figure 3.2: A collection of London newspaper articles summarizing the impacts of a hurricane in 1788. From upper left to lower right: Oct. 23rd Chronicle, Oct. 18th Bristol Journal, Nov. 14th Public Advertiser, and Oct. 7th Times.

While details of hurricane strikes in newspapers may not contain quantitative meteorological data, they can provide indications of the motion and intensity of tropical cyclones. Of the six primary chronologies, only Millás (1968) and Ludlum (1963) provide supporting evidence for their entries. For the August 1788 example, Millás details the history of the hurricane in the Caribbean (known as Hurricane San Rouge in Puerto Rico) while Ludlum focuses on impacts to the United States noting that the cyclone affected only a narrow region of the United States for an unusually short period of time. In addition to chronologies, a summary of the event is derived by Perley (1891) as well as several original newspaper articles.
Returning to Figure 3.2, information from the London Chronicle indicates that many Caribbean islands were not impacted by this hurricane and that the impacts were focused in the central portion of the Lesser Antilles and the island of Santo Domingo, known today as Hispaniola. The Bristol Journal indicates that the hurricane began in the central Leeward Islands during the evening of August 14th and was much worse on Martinique, which was likely closer to the center. The third entry from the Public Advertiser is an account of the hurricane in the United States, specifically Pennsylvania where heavy rains impacted the region and caused some damage. The article also states that rain was falling in the region two days before the hurricane struck, which may be indicative of a frontal boundary in the region. This may explain the unusual nature of the hurricane in the northeastern United States. The final newspaper featured an account from Port au Prince where twenty-five ships were missing in the region as a result of the hurricane.

In addition to newspapers and regional histories like Perley (1891), ship reports can provide critical information while the storm is located over the open ocean or near data sparse portions of the coastline. Unless found within one or the primary sources, ship reports are derived from the ICOADS database which provides individual ship information dating back over four centuries. For the pre-HURDAT era, these reports provide latitude, longitude, wind direction, and an estimate of wind speed. Returning to the 1788 hurricane, ship observations were used to identify the large area of high pressure over the eastern Atlantic and were important in the decision to list the hurricane as striking both the Caribbean and the northeastern United States. Specifically, a ship passing off the coast of Spanish Florida reported wind behavior associated with a cyclone passing to the east not the south as proposed by Chenoweth (2006). In
order to further demonstrate how chronologies and historical archives are used to estimate the tracks of tropical cyclones is presented in the next section.

3.4.1 Analysis of The Great Hurricane of 1780

The deadliest known Atlantic hurricane on record occurred in October 1780 and is still known today as simply The Great Hurricane. Due to the significance of this hurricane, it appears in most chronologies including Ludlum (1963) which focuses on the United States, a country not directly impacted by this hurricane. The track of this severe hurricane is described by many primary and secondary sources and is depicted or described in detail in Tannehill (1938) (Figure 3.1) among others. While these various sources describe the hurricane taking a similar track, there are several differences between them. Figure 3.3 shows the six different tracks for this hurricane including the “best track” that resulted from synthesizing all available data. The information that was used to make the track included chronologies, ship reports, newspaper accounts, and an excellent summary of the event in Reid (1838).
Figure 3.3: The “best track” of The Great Hurricane of 1780 (red line) and five other tracks done by previous historians.

The six tracks depicted in Figure 3.3 show how researchers using the similar information can produce different variations of the same event. Each description of the storm indicates that the hurricane formed well to the southeast of the Lesser Antilles and made landfall or passed very close to Barbados at nearly peak intensity before crossing the island chain somewhere in the vicinity of St. Lucia and Martinique (Figure 3.4). Ship reports indicate that the hurricane moved very slowly in the eastern Caribbean before passing over or very near the island of Mona located between Puerto Rico and Hispaniola. The storm then recurved in the vicinity of 70°W and passed some distance to the southeast of Bermuda on its way out into the open Atlantic. The differences
in tracks vary based on the interpretation of wind information and reports of damage on land. However, it is the lack of reports on certain that islands that may hold clues as to the true track of this hurricane.

**Figure 3.4:** Zoomed in version of Figure 3.3 with a red line highlighting the “best track”.

The Great Hurricane of 1780 appears to have taken a track that is more unusual than depicted by previous historians. We know that the hurricane took an unusually long time to traverse the eastern Caribbean, taking nearly a week to go from Barbados to Hispaniola. It would
appear based on weather reports throughout the Caribbean that the rate of motion was not constant and that the hurricane may have stalled and/or changed direction after passing into the Caribbean Sea. Both Reid (1838) and Tannehill (1938) assumed that the hurricane did not deviate significantly from a northwesterly track through the Caribbean but this fails to explain why thousands of people died on tiny St. Eustatius in the northern part of the Lesser Antilles. Ludlum (1963) and Norcross (2007) believe that the hurricane passed much closer to the northern Lesser Antilles but this fails to explain why Antigua, located approximately 75 miles to the east of St. Eustatius, received only minor damage and no reports of damage came from Montserrat or St. Croix which would have been seriously impacted. The track proposed in Millás (1968) attempted to compensate for both caveats but the track of the hurricane still does not pass close enough to St. Eustatius and St. Kitts to cause the level of destruction reported on these islands.

The track of The Great Hurricane proposed in this study was developed using several key ship observations from military vessels throughout the region. The log of the HMS Albemarle, stationed off the southwestern coast of Barbados, indicates that the hurricane passed just north of its location where northeasterly winds eventually shifted to the west and then south. The HMS Alcmene, located off the southwestern coast of Martinique, reported a gradual change in the wind direction as the eye of the hurricane passed very close to that island. Finally, the HMS Star located near Antigua reported four days of winds out of the east before shifting to the southeast on the 14th of October. Land reports indicate that the most severe damage from the hurricane came from Barbados, St. Lucia, St. Vincent, Martinique, southern Guadeloupe, St. Kitts, St. Eustatius, southwestern Puerto Rico, and southeastern St. Domingo (Hispaniola). It therefore seems reasonable that after passing Martinique and Dominica that the hurricane turned north
towards St. Kitts before abruptly turning towards the west and southwest and eventually northwest across extreme southeastern Hispaniola. While this is an atypical track for any tropical cyclone in the North Atlantic, similar behavior has been observed in other hurricanes. While additional information may be able to support or refute the track presented, it is clear that even the limited number of sources available can contain conflicting information. The process of how these various sources were combined into a database for further analysis is explained in the next section.

It is important to mention that the track of The Great Hurricane presented here is not a final or definitive track. This particular example is most likely the most discussed tropical cyclone in the entire pre-HURDAT era and a relative wealth of information is available for this case. Despite the amount of available data, there remains some uncertainty regarding this track and it may change when additional information, which is currently inaccessible, is obtained. This uncertainty level increases as the amount of available data decreases. In general, the tracks produced using this methodology have the highest level of confidence when over land.

3.5 Creation of the Master Database

Since some of the primary sources focus on a certain region of the North Atlantic basin, a master database is needed to construct a complete track for candidate tropical cyclones. This was done for the entire pre-HURDAT period and combined information from the seven primary sources. Data from each of the six chronologies was entered into six unique spreadsheet files and each entry was given an event number. Events that appeared in two or more chronologies were combined into a single entry in the master spreadsheet (Figure 3.5). The example that will be
used to illustrate this process will be the 1788 Western New England hurricane which appeared in all six chronologies. This event is entry number 141 but this listing has six additional event numbers associated with it corresponding to each chronology. Since HHIT entries contain tracks as opposed to a listing of locations, a column within the master spreadsheet is dedicated to that source which indicates if the candidate cyclone is also listed in that database. Data from additional sources are added to the master database but are not entered into a unique spreadsheet since some sources provide information for only a handful of tropical cyclones. An example of how the various data sources are merged together in the master database is shown in Table 3.3.

The next stage in data preparation is to determine if any of the sources contain erroneous or misleading data and attempt to determine which locations were directly impacted by the candidate cyclone. The example in Table 3.3 is for the “Western New England Hurricane” which impacted portions of the northeastern United States on August 19th, 1788 and has been linked to “Hurricane San Rouge” which impacted portions of the Caribbean Sea from August 14th-16th. Chenoweth (2006) lists this hurricane as two individual cyclones; Hurricane San Rouge dissipating after impacting Haiti on August 16th and a tropical storm (not a hurricane) impacting the United States a few days later. Millás also lists two entries for the cyclone but does not mention impacts on the United States. Ludlum believed that only one hurricane impacted both regions from August 14th-19th while Dunn and Miller (1960) does not contain information on the Caribbean. Finally, Tannehill (1938) and Poey (1855) list multiple entries for this storm and do not attempt to unite the entries. Additional supporting evidence from ship logs and overwash sediments in New Jersey (Donnelly et al., 2004) suggest that these cyclones should be classified as a single hurricane that made landfall in the Caribbean and the northeastern United States. This is how the two Chenoweth entries are entered in the master database.
Figure 3.5: Screenshot of the master database of candidate cyclones in this study. Primary sources are color coded and match the color scheme of Table 3.3.
Table 3.3: Listing of available sources for the third candidate cyclone of 1788.

<table>
<thead>
<tr>
<th>Source</th>
<th>Entry #1</th>
<th>Entry #2</th>
<th>Entry #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dunn and Miller</td>
<td>Entry 3: NH, MA, CT; Minimal Hurricane with 6 Deaths.</td>
<td>Entry 11: Eastern NY; Much damage in region.</td>
<td></td>
</tr>
<tr>
<td>Perley 1891</td>
<td>During the afternoon of August 19th, a gale impacted portions of western New England and eastern New York. The event lasted from around noon until approximately 4pm. There were reports of damage in southwestern CT, western MA, southern VT, and southwestern NH. Winds during the event were variable.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Summary of Ship Logs
Available observations on August 14th suggest that a large area of high pressure dominated the eastern Atlantic. A ship located between St. Kitts and Antigua reports a NE wind at 20mph, the outer edge of the hurricane. The same ship, located north of the Lesser Antilles on the 16th, gets caught in the tight pressure gradient between the hurricane and the Bermuda-Azores high. A ship moving just off the east Florida coast reports northerly winds as the hurricane moves well to the east. Finally, a ship located to the east of Boston reports strong winds from the south on August 19th. They are below tropical storm force.

Summary of Newspaper Accounts
From Millás: Guadeloupe and Martinique suffered from a gale the night of August 14th. Dominica saw much damage to sugar canes and provisions but damage was much worse in Martinique. St. Lucia did not suffer much and the hurricane did not impact Antigua which was suffering from a drought. The hurricane passed south of Puerto Rico and crossed Hispaniola from southeast to northwest on August 16th and 17th. A Spanish ship sunk in the western Bahamas.

From Various London Newspapers: The islands of St. Kitts, Antigua, Barbados, and St. Vincent escaped the hurricane while Hispaniola and Martinique suffered much. 25 vessels are missing at Port au Prince. The hurricane started at Dominica at 6pm (on August 14th) and increased in violence throughout the night. The hurricane was more severe at Martinique. Much damage was done to crops in Pennsylvania (on the 19th).

Result
Candidate Cyclone 88-3: Western New England Hurricane/Hurricane San Rouge
August 14th: Landfall in Martinique moving W
August 16th: Approaching Puerto Rico
August 18th: Moving rapidly towards the NNE
August 15th: Northeastern Caribbean Sea
August 17th: Impacting PR and Hispaniola
August 19th: US landfall; moving N rapidly

3.6 Creation of Spatial Datasets

Once all available data has been entered into the master database, the next step is to estimate six-hourly geographic positions for the candidate storm. Six hour intervals were chosen
to mirror the format of the HURDAT database. The geographic coordinates are preliminary estimates based on the available data. Table 3.4 lists the set of estimated geographic coordinates for our example whose track is depicted in Figure 3.6 using the Google Earth application. While this particular example lacked wind speed information, it was deduced that the center of this hurricane struck the island of Martinique shortly after midnight on August 15th and was moving due west since islands of Antigua to the north and Trinidad to the south did not report any impacts from the hurricane. The gathered information indicates that Puerto Rico felt the hurricane with most of the damage occurring in the southwestern part of that island. The cyclone crossed the island of Hispaniola from southeast to northwest on August 16th and 17th before moving rapidly to the north towards New England. The motion of the hurricane in the northeastern United States is estimated based on the acquired sources. Based on information in Perley (1891), it appears that the hurricane was undergoing extratropical transition which may explain why hurricane force conditions occurred in a narrow swath and for a very short duration.

Using the information from both the Caribbean and the United States as a guide, the spatial dataset was compiled and six-hourly coordinates were estimated. While the storm is near a landmass, qualitative observations, most notably wind direction and speed, are used to estimate where the tropical cyclone is located. For the periods of time when the hurricane was over the open ocean and no observations are available, it was assumed that the forward motion of the tropical cyclone was changing at a constant rate, in this case slowly increasing as it moved poleward. It is important to note that this assumption is based on a typical pattern associated with poleward moving tropical cyclones along the east coast of the United States. The forward motion of a tropical cyclone moving off the coast of eastern North America typically increases due to interaction with mid-latitude features, especially a large trough which is often located to the west
of the cyclone. Once these coordinates were estimated, they were entered into ArcGIS where multiple sets of coordinates can be displayed for further analysis (Figure 3.7). In addition to the ability to manipulate different attributes of the tropical cyclone tracks, ArcGIS is preferred over other software, such as Google Earth, because a spreadsheet of geographic coordinates can be imported as opposed to entering one at a time.

Figure 3.6: Track of the 1788 Western New England Hurricane/Hurricane San Rouge. White dots are 0z positions from August 15th, 1788 through August 19th, 1788.
Table 3.4: A list of geographic coordinates associated with the Western New England Hurricane/Hurricane San Rouge.

<table>
<thead>
<tr>
<th>Month</th>
<th>Day</th>
<th>Time</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>14</td>
<td>6</td>
<td>14.4</td>
<td>-55.5</td>
<td>TS</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>14.5</td>
<td>-57.1</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>18</td>
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<td>-58.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>0</td>
<td>14.6</td>
<td>-60.2</td>
<td>HU</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>14.6</td>
<td>-61.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>15.0</td>
<td>-64.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>15.7</td>
<td>-65.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0</td>
<td>16.6</td>
<td>-66.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>17.3</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>18.8</td>
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<td></td>
</tr>
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<td>20.1</td>
<td>-73.8</td>
<td></td>
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<td>-75.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>23.2</td>
<td>-76.0</td>
<td>HU</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>24.6</td>
<td>-76.5</td>
<td></td>
<td></td>
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<td>26.8</td>
<td>-76.9</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12</td>
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<td>HU</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>6</td>
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<td>18</td>
<td>45.1</td>
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<td>ET</td>
<td></td>
</tr>
</tbody>
</table>
Figure 3.7: The tracks of the 1788 hurricane and five other notable New England hurricanes.

3.7 Trends and Teleconnections

In the next chapter an analysis of the frequency of tropical cyclones in the North Atlantic is done and an attempt is made to link the patterns to three different teleconnections. For example, it has been shown that when the NAO is strongly positive, the probability of a tropical cyclone making landfall in the northeastern United States increases (Jamison, 2008). The NAO is a climatic “see saw” pattern between pressure systems in the North Atlantic Ocean. The strength of the NAO dictates the intensity of the Bermuda-Azores High which is one of the primary synoptic-scale features that guide the motion of tropical cyclones. In addition to the NAO, two other teleconnections for both the Atlantic (the AMO) and Pacific (the PDO) oceans will be reviewed.
The AMO is linked to changes in Sea Surface Temperatures in the North Atlantic which in turn impacts the breadth and depth of favorable ocean temperatures for tropical cyclogenesis. Inconsistencies exist, however, with respect to the specific role the AMO plays in establishing a favorable environment for increased tropical cyclone activity. Many scientists believe that the AMO is merely an artifact after detrending North Atlantic SST data back through the late nineteenth century. They make the claim that the observed pattern is a reflection of AGW and not an independent signal.

The PDO is a pattern in the SSTs of the North Pacific Ocean which was examined for possible patterns between the behavior of SSTs in the Atlantic and Pacific. The phase of the PDO is often compared with the phase of ENSO to see if they are independent of each other. Newmann et al. (2003) shows that the PDO is actually dependent upon ENSO on all time scales. It is then stated that the positive (warm) phase of the PDO is linked to the positive (warm) phase of ENSO which is associated with increased tropical cyclone frequency in the Northeastern Pacific Ocean and decreased activity in the Northern Atlantic. A positive phase of ENSO is linked with increasing wind shear over the Atlantic Ocean which results in fewer tropical cyclones.

Each index was reviewed on a yearly basis for the six months that traditionally delimit hurricane season (June-November) for every year data was available. A total of 155 years of data was available for the AMO, 111 years for the PDO, and 61 years for the NAO. Data was taken from the Earth System Research Laboratory for the AMO, the University of Washington for the PDO, and the Climate Prediction Center website for the NAO. Trends in each teleconnection, if any, were reviewed and compared with tropical cyclone frequency for their respective time periods to see if a correlation between the two existed and if it was statistically significant. For
the teleconnections with the highest correlation, a simple Spearman Rank Correlation test was done. This test was chosen because it was easy to sort the most active hurricane seasons from the least active by ranking the number of cyclones that formed in a particular year. However, since discrete numbers were used, there were many occasions where the rank was tied. The results of this study are presented in the next chapter.
Chapter IV: Results Part I: Pre-HURDAT Era Analysis

After completing an analysis of records from the seven primary sources the master database contained 475 entries, 408 of which were accepted as possible tropical cyclones. As stated in the previous chapter, entries were removed for a variety of reasons including duplicate entries, non-tropical entities, and those without supporting evidence. The more occasions a storm appears in one of the primary sources, the more likely it is a valid tropical cyclone. Table 4.1 splits the entries into categories based on how many times it appeared in one of the primary sources. On average, accepted entries appeared in 2-3 primary sources while rejected entries on average appeared in 1-2 of the sources. Despite only having one source, 122 entries were accepted into the database because that source provided sufficient details regarding the track and intensity of the tropical cyclone and/or were found in secondary source material.

Table 4.1: A listing of the number of sources that appeared in 1-6 of the primary sources.

<table>
<thead>
<tr>
<th>Sources</th>
<th>Accepted</th>
<th>Rejected</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>122</td>
<td>26</td>
<td>148</td>
</tr>
<tr>
<td>2</td>
<td>76</td>
<td>26</td>
<td>102</td>
</tr>
<tr>
<td>3</td>
<td>93</td>
<td>15</td>
<td>108</td>
</tr>
<tr>
<td>4</td>
<td>58</td>
<td>0</td>
<td>58</td>
</tr>
<tr>
<td>5</td>
<td>36</td>
<td>0</td>
<td>36</td>
</tr>
<tr>
<td>6</td>
<td>23</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td>Total</td>
<td>408</td>
<td>67</td>
<td>475</td>
</tr>
<tr>
<td>Average</td>
<td>2.7</td>
<td>1.8</td>
<td>2.3</td>
</tr>
</tbody>
</table>

While it is unlikely that enough information is available to reconstruct tracks for all 408 candidate tropical cyclones, this study has shown that tracks can be reconstructed for some of the
most notable tropical cyclones of the period. Table 1.1 showed us that 40% of the 30 deadliest
Atlantic hurricanes on record occurred prior to the commencement of the HURDAT database
including the deadliest hurricane on record, known simply as The Great Hurricane (1780). Using
the methodology outlined in the previous chapter, the tracks of The Great Hurricane and the two
other deadly hurricanes of October 1780 (Solano’s Hurricane and the Savannah-la-Mar
Hurricane which are ranked 22nd and 34th in terms of fatalities) were reconstructed (Figure 4.1).
The tracks of several additional reconstructed hurricanes used in the application study are
presented in Chapter 5.
**Figure 4.1:** A poster displaying information on the Great Hurricane in addition to the tracks of the Savannah-La-Mar Hurricane and Solano’s Hurricane based on information found in Millás (1968).

### 4.1 Long Term Trends

One of the most interesting scientific issues that have emerged in the past decade is the possible relationship between climate variability and change and tropical cyclone activity over
time. The debate regards whether or not the dramatic increase in the number of tropical cyclones observed since 1995, including a record number tropical cyclones in 2005, is due to natural variability in conjunction with our increasing ability to detect tropical cyclones or simply due to anthropogenic effects including the warming of the oceans. Knutson et al. (2010) reviews several studies on the issue but makes no definitive conclusions. Mann and Emanuel (2006) state that the existing record of annual counts for the Atlantic basin had a long term upward trend which they linked with an increase in Atlantic sea surface temperatures. However, Holland and Webster (2007) links this observed rise to the increase of greenhouse gasses while Solow and Moore (2002) find no trend in the counts of tropical cyclones. Knutson et al. (2010) state that the need for long term tropical cyclone databases for all oceanic basins is clear and that paleotempestological studies should be encouraged and supported as they will provide insight into the prediction of long term trends.

In response to the aforementioned debate, tropical cyclone counts were estimated for the pre-HURDAT era. Figures 4.2 and 4.3 show counts of all subtropical storms, tropical storms, and hurricanes for the period 1751-2010 which were made using a combination of HURDAT data and the results of this study. Tropical and subtropical cyclone counts for the period 1851-2010 were derived from the official HURDAT “best track” database (AOML, 2008) and counts for the pre-HURDAT era were appended to these values. Figure 4.2 shows the counts as a bar chart with both a trend line and a five year moving average. This figure does show that there is an increase in the counts of tropical cyclones over the last 260 years but also reveals what appears to be a multi-decadal trend in the frequency of tropical cyclones in the Atlantic basin. Figure 4.2 also shows that the most dramatic increase in frequency occurs in the late 1990’s and the early part of the last decade.
While Figure 4.2 does indicate a gradual rise in the counts of tropical cyclones, there are several patterns that emerge within this long term trend. The most tropical cyclones observed in the Atlantic basin occurred in 2005 when 28 were observed in the basin. However several other years stand out in the record and indicate that 2005 was not a singularity. This may indicate that the atmospheric and oceanic patterns that existed in 2005 have been and can be reproduced. The hurricane seasons in the record that show the most robust signal are 2005, 1969, 1933, 1887, and 1837 with an average 42 years between events.

In addition these years of “hyperactivity” we also see periods of increased hurricane activity followed by decreased activity. Looking at the five year moving average in the twentieth
century, we see a period of subdued activity from 1900-1931 followed by a sudden increase in activity from 1932-1971, a second period of relatively lower frequency from 1972-1995, and finally a dramatic increase starting in 1995. Figure 4.3 shows the same data from the bar chart in Figure 4.2 but in the form of a line graph. Areas of the line graph where increases in the annual frequency of tropical cyclones relative to other periods are observed are highlighted. Using Figures 4.2 and 4.3, it can be concluded that some multi-decadal pattern is evident and appears to exist in the century before the start of HURDAT as well. The possible relationships between the frequency of tropical cyclones in the Atlantic Ocean and various teleconnection patterns are reviewed in the following sections. For periods before the start of HURDAT, further analysis of the apparent multi-decadal trends will be performed once a more accurate count of pre-HURDAT tropical cyclones can be completed.
4.1.1 Tropical Cyclone Frequency and Teleconnections

The possible multi-decadal pattern in the frequency of tropical cyclones discussed in the previous section will be compared against trends in three different teleconnections. It has been well established that the El Niño Southern Oscillation (ENSO), most notably its positive phase, has an impact on the frequency of tropical cyclones in both the Atlantic and Eastern Pacific basins (Bossak and Elsner, 2001). In order to determine if other patterns existed between tropical cyclone frequency and teleconnections, the AMO, PDO and NAO were analyzed on an annual
basis using a mean average value for the June-November period. Of the three, the AMO showed the strongest signal and a simple Spearman Rank Correlation Test was done to both to see if the signal was statistically significant. It is important to mention that there are some caveats with using an average value of any of these teleconnections. A stronger signal may appear if the teleconnections are compared to tropical cyclone frequency on a seasonal or even monthly scale. Also, some of these teleconnections may have a lag meaning that the highest frequency of activity may not coincide with the corresponding extreme value in the teleconnection.

4.1.2 Tropical Cyclone Frequency and the AMO

Of the four teleconnections reviewed, the AMO not only appeared to have the best relationship to the frequency of tropical cyclones but also had the strongest correlation. Figure 4.4 compares the average annual June-November values of the AMO with the number of tropical cyclones. During the 155 year period, the AMO went through four pattern shifts where the average June-November values switched signs. The AMO was generally positive from 1856-1888, 1931-1960, and 1995-2010 which were periods of enhanced activity in the North Atlantic basin. In fact 9 out of 10 of the busiest Atlantic hurricane seasons occurred when the AMO was in its positive regime (1969 was in the negative regime but had an AMO value near zero) with an average value of 0.245 for the June-November period. While it appears that there is a relationship between the frequency of Atlantic tropical cyclones and the value of the AMO, there is only a very weak correlation ($R = 0.165$) between the strength of the AMO and the specific number of tropical cyclones that will occur in a given year. A simple Spearman Rank Correlation test was also done with a resultant value of 0.345 which is significant at the 0.01 confidence
level. In summary, it can be stated that some relationship exists between the phase of the AMO and the frequency of tropical cyclones in the Atlantic basin.

Figure 4.4: Tropical cyclone counts (Red) and the average June-November AMO values for 1856-2010 (Blue).

4.1.3 Tropical Cyclone Frequency and the PDO

While the PDO did not show a relationship that was as robust as the AMO, it appears that an inverse relationship does exist. Figure 4.5 compares the average annual June-November values of the PDO with the number of tropical cyclones. During the 115 year period, the PDO
went through three pattern shifts where the average June-November values switched signs. The periods where the AMO was in the positive regime generally correlate to the PDO in the negative regime. However, unlike with the AMO the average PDO values during the most active Atlantic hurricanes seasons was quite variable ranging from 1.907 to -1.545 in years that produced 17 and 16 tropical cyclones respectively. The PDO is considered positive when the value is greater than 0.5 while it is considered negative with the value is under -0.5 meaning that the PDO values were highly variable during the most active hurricane seasons. It appears that while an inverse multi-decadal relationship exists between the frequency of tropical cyclones and the PDO, the yearly variations of the two are not well correlated.
4.1.4 Tropical Cyclone Frequency and the NAO

An analysis of the NAO shows that there is no correlation ($R = 0.02$) and was the most variable of the three teleconnections. There appears to be no relationship between the specific number of Atlantic tropical cyclones and the value of the NAO though studies have shown that this teleconnection impacts the track of the tropical cyclones that form. Since a positive NAO results in a stronger Bermuda-Azores High, tropical cyclones are more likely to be pulled poleward along the periphery of the high pressure system possibly impacting the east coast of the United States. The opposite occurs during a negative NAO phase and tropical cyclones tend to
have more of a westerly component to their motion impacting the Caribbean and possibly the Gulf Coast region. According to the work done by Jamison (2008), the phase of ENSO also plays a role in the location a hurricane will make landfall (Figure 4.6).

**Figure 4.6:** A comparison of the phases of ENSO and the NAO and landfall regions (1900-2005) of the United States coast (From Jamison, 2008).
Chapter V: Results Part II: An Application of Pre-HURDAT Data

The objectives of this study are to develop a methodology for identifying and reconstructing historical tropical cyclone tracks (Chapter 3) and to show the utility of extending our hurricane database earlier by identifying preferred tracks of recorded landfalling hurricanes during two decades of the pre-HURDAT era and comparing them with two decades of the modern record. The eastern coast of the United States was chosen because a majority of the documents from the 1820s and 1830s have been preserved in addition to the large number of coastal population centers, which in 1820 stretched from St. Augustine in East Florida to Portland, Maine (Figure 5.1). The Gulf of Mexico region was excluded because with the exception of the port cities of New Orleans, Mobile, and Pensacola, the coastline of the Gulf of Mexico was sparsely populated in 1820 and it is possible that tropical cyclones, especially weaker tropical storms, stuck the region without being recorded. Shipping records were also more limited in this area and many of them required translation from French or Spanish. The 1820s and 1830s were selected because tropical cyclone activity was better recorded than in previous decades and featured several active hurricane seasons including at least thirteen hurricane landfalls along the eastern coast of the United States. This study will compare these decades with the 1950s and 1960s which featured a similar number of landfalls along the eastern United States including Carol (1954) and Edna (1954) in New England, Hazel (1954) in the Carolinas, King (1950) in Florida, and Donna (1960) along the entire study area. These two periods also featured similar landfall patterns with a high concentration of hurricane landfalls in the Carolinas.
For the period 1820-1839, 88 tropical cyclones were entered into the master database. From this group, a subset of 38 east coast tropical cyclones was extracted. Any entry that was clearly not strong enough to be classified as a hurricane based on available wind and damage information was removed leaving a total of 30 entries to be examined in depth. Of the remaining thirty entries, an additional 13 entries were removed because there was inadequate information to reconstruct a series of geographic coordinates and an additional entry was removed after analysis because it does not appear to be an east coast landfall as shown in the HHIT. Table 5.1 contains
information for the 17 pre-HURDAT hurricanes and 17 HURDAT hurricanes analyzed for this study.

Table 5.1: Landfalling east coast hurricanes used in this study and analyzed landfall location(s).

<table>
<thead>
<tr>
<th>Pre-HURDAT Hurricanes Name/Number (Year)</th>
<th>Location(s) Analyzed</th>
<th>HURDAT Hurricanes Name (Year)</th>
<th>Location(s) Analyzed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winyaw Bay Hurricane (1820)</td>
<td>NC</td>
<td>Hurricane King (1950)</td>
<td>FL</td>
</tr>
<tr>
<td>Norfolk &amp; Long Isl. Hurricane (1821)</td>
<td>NC NY</td>
<td>Hurricane Able (1952)</td>
<td>SC</td>
</tr>
<tr>
<td>Hurricane Three (1822)</td>
<td>SC</td>
<td>Hurricane Barbara (1953)</td>
<td>NC</td>
</tr>
<tr>
<td>Hurricane Two (1824)</td>
<td>GA</td>
<td>Hurricane Carol (1954)</td>
<td>NC NY</td>
</tr>
<tr>
<td>Early June Hurricane (1825)</td>
<td>FL NC</td>
<td>Hurricane Edna (1954)</td>
<td>MA</td>
</tr>
<tr>
<td>Hurricane Three (1825)</td>
<td>FL</td>
<td>Hurricane Hazel (1954)</td>
<td>NC</td>
</tr>
<tr>
<td>Great N. Carolina Hurricane (1827)</td>
<td>NC</td>
<td>Hurricane Connie (1955)</td>
<td>NC</td>
</tr>
<tr>
<td>Atlantic Coast Hurricane I (1830)</td>
<td>NC</td>
<td>Hurricane Diane (1955)</td>
<td>NC</td>
</tr>
<tr>
<td>Hurricane Three (1830)</td>
<td>ME</td>
<td>Hurricane Ione (1955)</td>
<td>NC</td>
</tr>
<tr>
<td>Hurricane One (1834)</td>
<td>NC</td>
<td>Hurricane Cindy (1959)</td>
<td>SC</td>
</tr>
<tr>
<td>South Florida Hurricane (1835)</td>
<td>FL</td>
<td>Hurricane Gracie (1959)</td>
<td>SC</td>
</tr>
<tr>
<td>Hurricane Two (1837)</td>
<td>FL</td>
<td>Hurricane Donna (1960)</td>
<td>NC NY</td>
</tr>
<tr>
<td>Hurricane Los Angeles (1837)</td>
<td>FL</td>
<td>Hurricane Cleo (1964)</td>
<td>FL</td>
</tr>
<tr>
<td>Calypso Hurricane (1837)</td>
<td>NC</td>
<td>Hurricane Dora (1964)</td>
<td>FL</td>
</tr>
<tr>
<td>Hurricane Thirteen (1837)</td>
<td>NC</td>
<td>Hurricane Betsy (1965)</td>
<td>FL</td>
</tr>
<tr>
<td>Hurricane Three (1838)</td>
<td>SC</td>
<td>Hurricane Inez (1966)</td>
<td>FL</td>
</tr>
<tr>
<td>Atlantic Coast Hurricane II (1839)</td>
<td>NC</td>
<td>Hurricane Gerda (1969)</td>
<td>ME</td>
</tr>
</tbody>
</table>

While meteorological observations during the pre-HURDAT era were scarce, we can use analogs of modern tropical cyclones to visualize the general synoptic pattern that prevailed when a hurricane made landfall. The tracks of the hurricanes listed in Table 5.2 were compared and those that made landfall in similar regions and approached from the same general direction were grouped together. The tracks of these hurricanes are depicted in Figure 5.2 (1820-1839 using archival data) and Figure 5.3 (1950-1969 using HURDAT data). While we can get reanalysis data for each individual hurricane, a more general picture of synoptic scale precursors to hurricane landfalls can be seen by constructing a composite of two or more hurricanes.
Composites of 500hPa geopotential heights overlaid with sea level pressure (SLP) were generated for five time periods, two days prior, one day prior, twelve hours prior, time of landfall, and twelve hours after landfall, for four different pre-HURDAT hurricanes. The sets of composites were generated using six-hourly data from the NCEP/NCAR reanalysis available on the Physical Sciences Division website.

Figure 5.2: HURDAT “best track” data for seventeen hurricanes from 1950-1969.
5.1 The 1821 New England Hurricane

The hurricane that would become known as the Norfolk and Long Island Hurricane was the first tropical cyclone of the 1821 Atlantic hurricane season. First detected north of Puerto Rico on September 1st, this fast moving and powerful hurricane passed north of the Bahamas, turned towards the north, and made the first of several landfalls about 20 miles east of Moorehead City, North Carolina late on September 2nd. The center stayed within 30 miles of the shoreline and was one of only two hurricanes ever to make landfall within the modern city limits of New York City, the other being the 1893 “Hog Island” Hurricane (Figure 3.7). The Norfolk
and Long Island Hurricane was likely of similar intensity to this hurricane at landfall in New York City since an overwash marker exists for this hurricane in New Jersey (Donnelly et al., 2004). Following a brief passage over Long Island, the hurricane made its final landfall in Connecticut and passed through New England and into Canada on September 3rd and 4th.

5.1.1 An Analysis of the 1821 Hurricane using Twentieth Century Data

This hurricane was selected because four hurricanes made landfall in New England during the 1950-1969 period. The tracks of Hurricanes Carol (1954), Edna (1954), Donna (1960), and Gerda (1969) were analyzed and compared to the 1821 hurricane (Figure 5.4). Of the four, Gerda made landfall in eastern Maine and was not considered in the composite because it tracked too far to the east resulting in a less robust and less centralized composite. While none of the twentieth century hurricanes made landfall as far west as the 1821 hurricane, the general synoptic pattern for each hurricane should be similar north of Cape Hatteras. It appears that all five of the hurricanes in Figure 5.4 were moving off towards the northeast at a rapid forward motion becoming extratropical after making landfall in New England.
Figure 5.4: Tracks of the 1821 hurricane (white) and the four possible composite members.

A reanalysis of the three New England hurricanes shows a quick transition at the synoptic level. Based on the information in Figure 5.5, we see that two days prior to the hurricane making landfall in New England, the Bermuda-Azores high dominates the eastern and central Atlantic and is centered in the vicinity of 45ºW. In the mid-latitudes, a generally zonal pattern quickly becomes increasingly meridional as the hurricane moves up the coast. A trough develops in the eastern Great Lakes region while the ridge over the Atlantic builds in response to the trough deepening. By twelve hours prior to landfall a strong geopotential height gradient has developed
and the hurricane follows this southwest to northeast orientated gradient which continues to intensify even after the hurricane has made landfall.

**Figure 5.5**: Composite time series for hurricanes Carol (8/31/54 at 12z), Edna (9/11/54 at 18z), and Donna (9/12/60 at 18z). Solid lines are SLP every 2mb and color contours are 500hPa geopotential heights every 50m. Time series from top left to bottom right are: 48 hours (a), 24 hours (b), and 12 hours (c) before landfall, the time of landfall (d), and 12 hours after landfall (e).
5.1.2 Reconstructing the Synoptic Environment of the 1821 Hurricane

Now that a general overview of the possible synoptic pattern associated with 1821 hurricane has been ascertained, the final step is to use available information to attempt to recreate the synoptic pattern in 1821. In order to verify the situation presented in Figure 5.5, we need to prove that a large area of high pressure existed over the central Atlantic while the 1821 hurricane was south of New England (Figure 5.5d). Unfortunately, sources for any specific time are limited and not every source will contain information regarding the direction or speed of the wind. For reports on land, a summary of the hurricane found in Ludlum (1963) is utilized while the ICOADS database is used to find ship reports. The selected time for this study is September 3rd, 1821 at 6pm which is the point when the hurricane was rapidly approaching New York City from the southwest. These reports are summarized in Figures 5.6 and 5.7 and the details of these reports are in Table 5.2.
Figure 5.6: Locations of the thirteen available meteorological observations for 6pm on September 3rd, 1821 with specific details for the three ship reports.
Figure 5.7: Wind direction at ten land locations taken around 6pm on September 3rd, 1821. At this time, the hurricane is centered over New Jersey and will pass directly over New York City within the next two hours.
Table 5.2: Meteorological information for the 1821 hurricane at 6pm on September 3rd, 1821.

<table>
<thead>
<tr>
<th>Location</th>
<th>Wind Direction</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.60N 36.67W</td>
<td>North</td>
<td>Light winds and seas</td>
</tr>
<tr>
<td>36.83N 48.05W</td>
<td>-</td>
<td>Calm winds and seas</td>
</tr>
<tr>
<td>32.43N 63.36W</td>
<td>East-Northeast</td>
<td>Brisk winds and rough seas.</td>
</tr>
<tr>
<td>Williamstown, MA</td>
<td>Southeast</td>
<td>Violent wind with rain.</td>
</tr>
<tr>
<td>Litchfield, CT</td>
<td>Southeast</td>
<td>-</td>
</tr>
<tr>
<td>New Haven, CT</td>
<td>Southeast</td>
<td>Winds gradually increasing.</td>
</tr>
<tr>
<td>Bridgeport, CT</td>
<td>Southeast</td>
<td>Weather quickly deteriorating.</td>
</tr>
<tr>
<td>New York City, NY</td>
<td>East</td>
<td>Approaching lowest pressure.</td>
</tr>
<tr>
<td>Newark, NJ</td>
<td>Northeast</td>
<td>Winds approaching peak intensity.</td>
</tr>
<tr>
<td>Cape May, NJ</td>
<td>Northwest</td>
<td>Weather slowly improving.</td>
</tr>
<tr>
<td>Philadelphia, PA</td>
<td>Northwest</td>
<td>Violent wind and rain.</td>
</tr>
<tr>
<td>Poplar Island, MD</td>
<td>Northwest</td>
<td>Weather quickly improving.</td>
</tr>
<tr>
<td>Norfolk, VA</td>
<td>Northwest</td>
<td>Storm ended several hours prior.</td>
</tr>
</tbody>
</table>

Despite the small amount of available information, it was possible to estimate the locations of both the 1821 hurricane and the Bermuda-Azores high. The wind behavior of the ten meteorological observations in the northeastern United States clearly indicates the counterclockwise rotation around the center of the hurricane. The center of the hurricane was placed in south-central New Jersey because the weather in Newark and New York City was approaching peak intensity while conditions at Cape May were slowly improving. The specific location in New Jersey was selected because conditions in Philadelphia, located to the west of the track, were described as “violent” at this time indicating that the hurricane was near its closest
approach to that city. Three conveniently placed ship observations also hint at the presence of a large Bermuda-Azores high. The first ship observation comes from the north Atlantic to the west of the Azores and reported northerly winds and light sea which indicate that this ship was on the easterly periphery of the high pressure. The second observation was located near the center of the high pressure as evidence by nearly calm winds and light seas. The final observation was located near Bermuda and reported brisk east-northeast winds and rough seas. This location is likely located on the southwestern fringe of the high pressure and is experiencing increased winds due to the pressure gradient between the high and the hurricane.

While the available observations are useful in estimating the locations of pressure centers, there are many caveats to consider. The primary issue is that the information retrieved is generally qualitative and exact wind measurements were unavailable in 1821 and temperature and pressure measurements were rare. Another caveat is that only three observations were used to estimate the conditions over the entire central Atlantic. In general, the lack of additional information is a problem and a complete picture of the synoptic situation cannot be done until these observations are obtained. The observations gathered are only a fraction of those that are available but are unobtainable without traveling to distant locations or paying a fee. A significant amount of information exists in library collections in North America and Europe that other researchers such as Michael Chenoweth and Cary Mock have utilized.

5.2 Comparing Similar Pre-HURDAT Hurricane Tracks

The early 1820’s was an active period for the eastern United States with at least six hurricanes making landfall (Table 5.1) including a landfall in South Carolina in 1822 and one in
Georgia in 1824 which may have been a major hurricane (Figure 5.8). While both hurricanes had an initial track towards the Georgia coast, the 1822 hurricane veered off to the north prior to landfall. This next case study compares the composites for each hurricane to see if any significant differences in the synoptic pattern are apparent. A study such as this may be particularly important for the state of Georgia which has not seen a landfalling hurricane of greater than Category 2 intensity since the late nineteenth century when Hurricane Seven made landfall as a Category 4 hurricane on October 2nd, 1898.

Figure 5.8: Tracks of the 1822 South Carolina hurricane and 1824 Georgia hurricane.
Composites attempting to recreate the general synoptic environment in 1822 and 1824 were created using the same procedure as the previous case study. For the 1822 hurricane, the tracks of Hurricane Hazel (1954) and Hurricane Cindy (1959) were analyzed. These hurricanes formed in different regions of the basin (Hazel in the Caribbean, Cindy north of the Bahamas) but both eventually made landfall in the Carolinas before accelerating off to the north. Hazel made landfall near the border of North and South Carolina while Cindy made landfall along the central South Carolina coast. Unlike in the New England case study, the composites were dominated by one hurricane, in this case Hazel, but still produced a simulation that was close to the 1822 hurricane north of the Bahamas.

While the coast of Georgia was not struck by a hurricane during the 1950s and 1960s, Hurricane Able (1952) and Hurricane Gracie (1959) made landfall in southern portions of South Carolina. These two hurricanes, most notably Able, had tracks similar to the 1824 hurricane but turned towards the north shortly before landfall. Hurricane Able originated near the Cape Verde islands and passed well to the north of the Bahamas as a minimal hurricane before taking a sharp turn to the north and making landfall near Beaufort, South Carolina. Hurricane Gracie meandered to the east and northeast of the Bahamas for nearly a week before rapidly intensifying and slamming into Beaufort, South Carolina as a Category 4 hurricane. These hurricanes were selected because of their similar landfall location which is approximately 30 miles from the Georgia border and 40 from the major city of Savannah, Georgia. The results of the composites for the 1822 hurricane and 1824 hurricane are shown in Figure 5.9 and Figure 5.10 respectively.
Figure 5.9: Composite time series for hurricanes Hazel (10/15/54 at 12z) and Cindy (7/9/59 at 6z). Solid lines are SLP every 2mb and color contours are 500hPa geopotential heights every 50m. Time series from top left to bottom right are: 48 hours (a), 24 hours (b), and 12 hours (c) before landfall, the time of landfall (d), and 12 hours after landfall (e).
Figure 5.10: Composite time series for hurricanes Able (8/31/52 at 0z) and Gracie (9/29/59 at 18z). Solid lines are SLP every 2mb and color contours are 500hPa geopotential heights every 50m. Time series from top left to bottom right are: 48 hours (a), 24 hours (b), and 12 hours (c) before landfall, the time of landfall (d), and 12 hours after landfall (e).

Based on the information from the composites, it does appear that there are several differences between the synoptic precursors associated with these hurricanes. Two days prior to landfall, a strong area of high pressure is located south of Newfoundland, which is farther west than in the previous case study. The most notable difference between the two is the position of the trough off to the west. While the 500mb trough is apparent in the first case, it is nonexistent in the second case. The areas of high pressure and associated maxima in Geopotential heights are also weaker in the first case. Therefore, it appears that the combination of an approaching trough and a weaker ridge aided in the poleward motion that allowed hurricanes Hazel and Cindy to
make landfall further up the coast. In the future when more data is acquired, it may be possible to visualize the differences in these patterns at the surface.

### 5.3 The 1837 “Havana to Hatteras” Hurricane

The most active individual year of the pre-HURDAT era occurred in 1837 when thirteen possible tropical cyclones have been uncovered (Figure 5.11) including at least four hurricane landfalls along the United States east coast (Table 5.1). The last of these hurricanes was the only one to make a direct landfall on the state of North Carolina but was the fourth to have a notable impact on the Tar Heel state. Prior to this final hurricane, the Outer Banks region of North Carolina was also impacted by the Calypso Hurricane and Hurricane Eight in August as well as Racer’s Storm in early October. Extending out into the Atlantic, the coastline of eastern North Carolina is more vulnerable to hurricane landfalls and it is common for these tropical cyclones to either brush southeastern New England or pass out to sea after impacting the state which is what happened with the thirteenth hurricane of the 1837 season.
The final hurricane of the season severely impacted Cuba as a major hurricane before moving through the Bahamas and northward towards eastern North Carolina. First noticed on October 18th, this hurricane caused considerable damage in Cuba where it was likely a major hurricane at landfall late on October 25th. The hurricane was still potent when it struck the Bahamas on October 27th and 28th and began to accelerate towards the north-northeast. From late on October 29th until the 31st, the weakening hurricane struck the Outer Banks and turned towards the northeast passing well to the south of New England. Based on this knowledge, it was
assumed that the composites would reveal that an approaching trough and associated mid-latitude cyclone would be responsible for path taken by the 1837 hurricane.

5.3.1 An Analysis of the 1837 Hurricane using Twentieth Century Data

A composite attempting to recreate the general synoptic environment for the last hurricane of 1837 was created using the same procedure as the previous case studies. In this case, the tracks of Hurricane Barbara (1953) and Hurricane Ione (1955) were analyzed. While both hurricanes came from the southeast instead of the south, they both made landfall in eastern North Carolina before passing out to sea. The track of Barbara is almost identical to the 1837 hurricane near landfall while Ione follows a similar track out to sea and south of New England. Figure 5.12 depicts the tracks of the three hurricanes near the coast of the United States.
A review of the composites for the North Carolina hurricanes is shown in Figure 5.13 and produced some unexpected results. It appears that the synoptic pattern is dominated by a large dome of high pressure located to the south of Newfoundland two days prior to landfall. While this was approximately the same location as the earlier series of composites, it is much stronger in this scenario. Like the previous cases, we see a transition to a more meridional pattern, though the trough is weaker than predicted. In a reconstruction of the 1837 hurricane, we would expect to see the strong ridge break down over the eastern United States allowing the hurricane to move almost due north. We would also be looking for a cold front approaching from the west which would prevent the storm from continuing north and into New England. An attempt to reconstruct the synoptic situation over the Atlantic basin was made however there were even fewer
observations available than with the previous case studies and there was only enough information available to estimate the track of this hurricane as opposed to also identifying larger synoptic-scale features.

Figure 5.13: Composite time series for hurricanes Barbara (8/14/53 at 0z) and Ione (9/19/55 at 12z). Solid lines are SLP every 2mb and color contours are 500hPa geopotential heights every 50m. Time series from top left to bottom right are: 48 hours (a), 24 hours (b), and 12 hours (c) before landfall, the time of landfall (d), and 12 hours after landfall (e).
5.4 Discussion

This study attempted to use a combination of reanalysis data and historical data to reconstruct the general synoptic pattern for four nineteenth century hurricanes that made landfall along the east coast of the United States. While composites were made for each case study, there was not adequate data to properly reconstruct the synoptic overview for all but the first case study. However it is known that more data, from both the mainland and the ocean, exists and work will be done in the future to acquire the needed documents. With more observational data, it will be easier to estimate the center of the hurricane and to identify other large scale features.

While it is obvious that we will never know the exact synoptic situation in the upper levels of the atmosphere, we can use ship logs and land reports to deduce what surface features were apparent during this period. Using twentieth century composites to reconstruct the nineteenth century synoptic environment can improve the accuracy of the historical tropical cyclone tracks, especially while the tropical cyclones are over water and distant from shipping lanes. In the first case study, an analysis was done on the 1821 Norfolk and Long Island hurricane. While sufficient data was available for this event, only three ship logs were available through the ICOADS database. After reconstructing what the synoptic environment could have looked like in early September 1821, these observations supported the large area of high pressure over the eastern and central Atlantic. From what information was gathered thus far, it appears that composites of twentieth century hurricanes can be used to analyze the synoptic precursors of nineteenth century landfalling hurricanes though more exploration should be done on the topic.
Chapter VI: Conclusions and Future Work

The purpose of this study is to outline a methodology for taking mainly qualitative archival information and reconstructing the tracks of historical tropical cyclones. This research showed that it is feasible to do an analysis of hurricane seasons prior to the start of the HURDAT database. To accomplish this, an application study was done comparing landfall patterns associated with similar landfalling east coast hurricanes in the pre-HURDAT period (1820s and 1830s) and the modern record (1950s and 1960s). The frequency of Atlantic tropical cyclones was also examined for long term trends and compared to several teleconnections.

The application study showed that it may be possible to use twentieth century analogs to estimate the synoptic environment of pre-HURDAT tropical cyclones. A composite of three 20th century New England hurricanes showed that in 1821 a large and displaced Bermuda-Azores high should be present over the central and eastern Atlantic. While available ship data was very limited, observations do indicate a large area of high pressure in the expected location. The second study used 20th century data to determine if there was any significant difference between the synoptic patterns associated with an 1822 landfalling hurricane in South Carolina and one that struck Georgia two years later. It appears that a stronger ridge to the northeast of the Georgia hurricane is the primary catalyst that resulted in a landfall further to the south. The final case study examined a North Carolina hurricane and showed that this hurricane likely recurved out to the open North Atlantic without impacting New England because of an approaching frontal system.
It was found that while the frequency of tropical cyclones in the Atlantic is increasing, there appears to be a clear cyclical pattern. When frequency was matched with the phase of various teleconnections, it was found that a possible link exists between the phases of the Atlantic Multidecadal Oscillation and the general level of tropical cyclone activity. There may also be a weaker inverse association between the Pacific Decadal Oscillation as well. Two other teleconnections were compared to the frequency of tropical cyclones but produced no significant correlations. Further research needs to be done to confirm these observations and the frequency of tropical cyclones should also be compared to other patterns.

6.1 Future Work and Applications

In the future, the master database will be expanded with additional digitized resources that have become available to the public over the past decade. Once these documents are acquired, track reconstructions can be attempted for each individual entity. These new track constructions will be overlaid on maps with reconstructed political boundaries and colonial claims for the year the tropical cyclone existed. This will be particularly important early in the pre-HURDAT era when most of the western hemisphere was under the control of a European power. Similar to the HHIT, metadata files containing the information used to reconstruct the tropical cyclone tracks will be available. Once tracks have been completed for the entire pre-HURDAT era, an online database will be made for public access. For the tropical cyclones that have already been analyzed, new data can be used to update tracks so that we have the most comprehensive set of geographic coordinates available. For the 91 HHIT tracks, future work can
be done to expand these tracks beyond the scope of the American mainland as many of these cases impacted the Bahamas and/or the Caribbean Sea before impacting the United States.

The ultimate goal of this and other paleoclimate studies is to extend our official hurricane database backwards in time to cover the early nineteenth century and perhaps the other earlier centuries. An ongoing project at the NOAA Hurricane Research Division is a reanalysis of the HURDAT database which has been completed for the period 1851-1930. This revision was brought about for several reasons including the correction of errors, removal of biases, and the addition (and occasionally a reduction) of tropical cyclones (Landsea et al., 2004). All changes to the official database, including future extensions backward in time, have to be approved by the NHC Best Track Change Committee, a body of individuals tasked with approving all alterations to HURDAT. An alteration is made only if there is sufficient evidence contesting the original database. In some instances, a candidate tropical cyclone will be turned down by the committee if they do not believe the evidence provided is enough to classify it as a tropical cyclone. Future additions to HURDAT prior to 1851 will undergo extreme scrutiny and most of the entries in the master database currently do not contain enough information to be added to HURDAT. However, the information is available and it is likely that HURDAT will be expanded backwards in time to at least an additional fifty years.

Even though the results of this study cannot be immediately incorporated into HURDAT, there are other uses for this study. In addition to the possible benefits to researchers, extending the hurricane database backwards in time will be valuable to the public as well. In the emergency management field, an understanding of potential hazards to a population is a critical part of the preparedness practice. With its concave shoreline, the state of Georgia rarely experiences the direct impacts associated with tropical cyclones. Due to this fact, the residents of the city of
Savannah believe that they are less likely to see a landfalling hurricane. According to HURDAT records, no major hurricanes made landfall along the Georgia coast in the twentieth century. However, initial results of this study indicate at least two major hurricane landfalls (the 1804 Antigua-Charleston Hurricane and the 1824 Georgia hurricane discussed in Section 5.2) in addition to the three recorded in the 1851-1899 period. This indicates that not only the city of Savannah but the entire coastline of Georgia should be better prepared for the next major hurricane landfall.

This information will also be valuable for members of the insurance and reinsurance fields who can better access the threat to properties along vulnerable shorelines. Located well north of the tropics, most people do not associate New York City with tropical cyclones and their hazards though this city has experienced such a disaster. According to the New York City Office of Emergency Management, one of the only hurricanes to ever pass directly over the modern city limits of New York occurred on September 3rd, 1821, when the East River converged with Hudson River across lower Manhattan as far north as Canal Street (NYC OEM, 2011). Since our official database begins thirty years after this event, the exact track of the hurricane is currently not known but a “best track” of this hurricane was constructed in this study. On average, hurricanes that make landfall in the northeastern United States have a mean velocity of 33mph (Vallee, 2000) giving emergency managers little time to evacuate a population as massive as the New York. Future research will identify coastal regions of the eastern United States that many believe are less vulnerable to hurricanes which will assist emergency managers in properly preparing citizens and avoiding the loss of life association with the inundation of New Orleans during Katrina. In summary, a backward extension of the HURDAT database is not only needed
but has many potential benefits to both researchers and the general public as reconstructions of historical tropical cyclones can be done using archival information.
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