THE FLORIDA STATE UNIVERSITY COLLEGE OF SOCIAL SCIENCES

EARLY 19th CENTURY U.S. HURRICANES: A GIS TOOL AND CLIMATE ANALYSIS

By

BRIAN H. BOSSAK

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The members of the Committee approve the		
Dissertation of Brian H. Bossak defended on March 26, 2003:		
	James B. Elsner Professor Directing Dissertation	
	Xufeng Niu Outside Committee Member	
	E. Jay Baker Committee Member	
	R. Dan Jacobson Committee Member	
Approved:		
Barney Warf, Chairperson, Department of Geography		
The Office of Graduate Studies has verified and approved the above named committee members		

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ABSTRACT

Hurricane climate research is based on data spanning the last 100 years or so. To better understand rare but potentially catastrophic hurricane events it is helpful to have longer records. Records from historical archives are available, but they need to be collated and edited. Efforts to collate U.S. tropical cyclone information from the first half of the 19th Century using a Geographic Information System (GIS) have been conducted in this research. The Historical Hurricane Impact Tool (HHIT) is based on Environmental Systems Research Institute's (ESRI) Arc View GIS 3.1. Statements concerning coastal and near-coastal impacts are reproduced within map callout boxes. The callout boxes point to the geographic location of the documented information. Map layers are used for different archival sources. The HHIT, which is available in hardcopy format and will be online in the near future via an internet map server, can be used by scientists, emergency managers, and the general public to better estimate the risk of a hurricane catastrophe.

The U.S. hurricane database ('Best-Track'') was recently extended from 1871 back to 1851 through the work of NOAA's Atlantic Hurricane Reanalysis Project. In addition, the previously mentioned Historical Hurricane Impact Tool (HHIT) has been utilized to collate and list recorded U.S. hurricanes back to the year 1800. The combination of NOAA's 'Best-Track' data back to 1851 and the HHIT collated hurricane list back to 1800 provide an unprecedented look at U.S. hurricane activity since the beginning of the industrial revolution. This research also examines U.S. (major) hurricanes over four 50-year epochs, and then further examines regional trends in U.S. hurricanes. Seasonal distributions are similar across epochs. The earliest epoch contains the greatest ratio of major hurricanes to all U.S. hurricanes. Each epoch is further divided into three separate regions, and hurricane landfalls in Florida and the East Coast region are found to have an inverse relationship. Furthermore, the relationship between climate variables such as ENSO, the NAO, the PDO, and U.S. hurricanes is determined to possibly be different in the first epoch (1801-1850) than in the other three epochs (1851-2000). The relationships noted are robust to changes in sample size. A physical explanation for the noted

trend is presented in a later chapter. Other climate influences on U.S. hurricanes, including volcanic eruptions and sunspots, are explored for effects on landfall counts.

CHAPTER 1

INTRODUCTION

Hurricanes are among the most dangerous and damaging storms on Earth (Malilay 1997). They have the potential to cause as much damage and loss of life in the United States as earthquakes (Diaz and Pulwarty 1997). Recent estimates put the average annual cost of hurricane damage in the U.S. at \$4.8 billion dollars (Pielke and Landsea 1998). Encompassing a diameter of between 200 and 1300 kilometers and possessing a wind velocity of 33 ms⁻¹ (74 mph), hurricanes are capable of inflicting widespread destruction. Hurricanes create physical hazards including extremely high winds, torrential rains, and storm surge. In addition, hurricanes generate secondary hazards such as electrocution, CO (carbon monoxide) poisoning, and house fires. As a consequence, it is important to understand how often hurricanes occur and at what intensity.

Hurricane intensities are classified on the Saffir-Simpson scale (Saffir and Simpson 1974) (Table 1). The scale arranges storms by physical characteristics including central pressure, wind speed, and damage potential. Hurricanes with wind speeds > 49 ms⁻¹ (>110 mph) are classified as major hurricanes. A hurricane that makes at least one landfall on the U.S. coastline is called a U.S. hurricane. A landfall occurs when all or part of the eye wall (which is the central ring of deep atmospheric convection, he avy rainfall, and strong wind) passes directly over the coast or adjacent barrier island. Historically, major hurricanes have caused 83% of all U.S. hurricane damage, but represent only 21% of landfalling tropical cyclones (Pielke and Landsea 1998). On average, the United States gets hit by approximately 5 hurricanes in any 3 year period and by 5 major hurricanes in any 8 year period.

Exposure to hurricane damage is a function of the population at risk, property at risk, and the level of preparedness (Pielke and Pielke 1997; Gibney 2002). The

vulnerability of the U.S. coastline to hurricane damage (both economic and in terms of loss of life) is increasing due to the large swell in population along the coastline. Currently, approximately 45 million people live along the coast from Brownsville, TX to Eastport, ME (Elsner and Kara 1999). In fact, Elsner and Kara (1999) note that "[i]ncreases in population have far exceeded improvements in forecasts of a hurricane's track and intensity changes" and that "[a] scenario featuring mass casualties from a hurricane continues to be a real threat along much of the U.S. coastline" (p. 384). Arguez and Elsner (2001) note that despite the reduction in the average number of deaths due to U.S. hurricanes in the last century, the median number has increased in the second half of the twentieth century. They suggest that part of the reason for this increase is the rise in U.S. coastal population (The population of the U.S. coastline between Texas and North Carolina rose 80% between 1960 and 1994). As coastal population increases, the economic damage potential increases as well. For example, \$3.1 trillion worth of coastal property was insured in 1993, compared to \$1.9 trillion in 1988, a 69% increase in 5 years (Pielke and Pielke 1997). Thus, hurricanes pose a serious threat to the United States in both economic and human terms and better long-term risk assessments are needed.

Tropical cyclones develop in portions of the North Atlantic basin with a large region of sea surface temperatures higher than 26.5°C (generally west of 20°W longitude andnorth of 10°N latitude), an atmosphere that contains abundant water vapor, and sufficient cooling with height in the troposphere (lapse rate). Factors that help encourage tropical cyclone intensification and development include a minimum latitude above the equator of 8°, weak vertical shear through the trade winds, and some pre-existing atmospheric disturbance (Elsner and Kara 1999). In many cases, not all of these conditions are present in the North Atlantic, and tropical cyclone activity is thereby subdued.

The uncertainty surrounding coastal hurricane risk assessment is compounded by the prospect of climate change. Projections of the amount of global warming change with improvements in model resolution and sophistication. IPCC (Intergovernmental Panel on Climate Change) assessments in the mid-1990's indicated that surface temperatures have warmed by 0.3 to 0.6°C since 1900 and that a further increase of between 1 and 3.5°C is possible before the year 2100 (UNEP/WMO-IPCC 1995). More recent simulations of

global climate change between 2000 and the year 2100 revise these predictions higher. An IPCC report issued in 2001 projects surface temperatures for the year 2100 to be between 1.4 and 5.8°C above current global surface temperature averages (UNEP/WMO-IPCC 2001). This rate of global surface warming would be unprecedented in the last 10,000 years, as inferred from paleoclimatic data.

The impact of global warming on tropical cyclone formation (including hurricanes) remains unknown (Landsea 2000). Regional studies of tropical cyclone activity provide little evidence either way (Landsea et al. 1996; Bove et al. 1998a; Smith 1999; Avila and Pasch 1997; Chan and Shi 1996) and some studies indicate a tendency for active years in one region to be offset by inactive years in other regions (Elsner and Kocher 2000). Nott and Hayne (2001) state that longer-term records of tropical cyclone activity are necessary in order to conduct more definitive research regarding anthropogenic changes to climate and tropical cyclone development.

The majority of hurricane climate research is based on records spanning the last 100 years or so (Elsner et al. 2000a; Landsea et al. 1996). Less reliable, but still useful information is available back to the beginning of the 19th century. Historical documentation on early American hurricanes are underutilized. Historical accounts of hurricane occurrence and landfall exist in a variety of documents that include compendiums sorted by region and date, documents which analyze records for individual states, and personal research. Information sources in these works include observations, ship records, newspaper accounts, and personal letters. Some sources include governmental archive reports. For several reasons, this collection of hurricane information has not been utilized as scientific evidence pertaining to early American hurricanes. First, the information exists in various and scattered archives and extensive work is needed to access and collate this information. Second, the information has, for the most part, not been mapped, and the geographic context of the information has not been emphasized. Finally, in many cases, the documents contain little quantitative information. Although there is little that can be done to solve the problem of missing quantitative information, collating and mapping the existing records helps to quantitatively describe the spatial dimension of the storm's impact. Knowledge of the

past occurrence of U.S. hurricane landfalls, even if incomplete, provides clues about future frequency and intensity (see Elsner and Bossak 2001).

The first section of this dissertation reports on efforts to collate documental evidence of past hurricanes for the period 1800-1850. This period was chosen because it represents the years prior to the NOAA best-track dataset which begins with the year 1851. The purpose is to bring together various historical archives into a single electronic reference source and to add value to the archives by mapping the information contained within using Arc View GIS. Where available, quantitative data are included in the descriptive callout boxes. Historical hurricane accounts (textual documents) are accessible to scientists, emergency managers, and others interested in descriptions of early American hurricanes. The result of this collation and mapping, called the Historical Hurricane Impact Tool (HHIT), can be utilized for statistical analysis and for comparisons with modern records. Moreover, information can be edited, updated, or modified for specific purposes. This work considers only hurricanes affecting the mainland United States and not tropical cyclones that remained at sea.

In addition, trends in U.S. hurricanes, including landfall numbers, geographic location of landfalls, seasonal distributions, and major hurricane counts over the past 200 years are examined. The 200-year history is divided into non-overlapping 50-year epochs and compare activity across epochs. Moreover, the overriding goal of the research is to determine if the influence of climate features such as El Niño (La Niña)-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO) can be detected in the early U.S. hurricane records and examine the results for similarity with later records. This research is especially targeted to determine if climate influences on U.S. hurricanes have shifted in dominance over the last 200 years as additional evidence of climate change. Additional investigations of the influence of extraterrestrial (sunspot cycles) and geologic (volcanic eruption) activity on U.S. hurricane counts are conducted.

A key finding of the present analysis is that the variables influencing coastal hurricane activity appear to change over time. The dominant modes of influence on U.S. hurricanes appear to shift with the NAO and ENSO becoming much more important through the 20th century as opposed to their influence in the 19th century. In contrast, the

PDO appears to have had a greater influence on U.S. hurricanes through the 19^{th} century, with a much-lesser influence through the 20^{th} century. Furthermore, sunspots and volcanic activity are found not to be statistically significant in explaining U.S. hurricanes.

TABLE 1. Saffir-Simpson Hurricane Scale (adapted from Pielke and Pielke 1997).

Category	Pressure (mb)	Pressure (in/hg)	Winds (mph)	Winds (m s ⁻¹)	Surge (feet)	Surge (meters)	Damage
1	980	28.92	74-95	33-42	4-5	1-1.5	Minimal
1	960	20.92	74-93	33-42	4 -3	1-1.5	Willianai
2	965-979	28.50-	96-110	43-49	6-8	2-2.5	Moderate
2	705 717	28.91	70 110	15 17	0 0	2 2.3	Wiodelate
3	945-964	27.91-	111-130	50-58	9-12	3-3.5	Extensive
		28.49					
4	920-944	27.17-	131-155	59-69	13-18	4-5.5	Extreme
		27.90					
~	₄ 0 2 0	-27.17	. 155		. 10		C 1:
5	<920	<27.17	>155	>69	>18	>5.5	Catastrophic

CHAPTER 2

DOCUMENTS OF EARLY AMERICAN HURRICANES

2.1 Ludlum's Monograph

Descriptions of hurricanes have been captured in eyewitness accounts for hundreds of years. While the post-WWII period is considered the most accurate (Elsner and Kara 1999; Landsea et al. 1999), historical records in the North Atlantic date back to 1492. Several sources are considered high-quality tropical cyclone histories. These include the early works of Garriott (1900) and Fassig (1913). The later works of Tannehill (1956) and Dunn and Miller (1960; 1964) also provide comprehensive accounts of North Atlantic tropical cyclone activity. The most comprehensive compilation of evidence on early American hurricanes is provided by Ludlum (1963). His monograph contains descriptions of storms affecting the American coast line during the period 1492-1870 and is based in part on earlier chronologies. The monograph begins with a description of tropical cyclones that affected the expeditions of Christopher Columbus. It contains a section describing storms that struck the present-day U.S. coastline between 1501 and 1700. The records of hurricane and tropical storm occurrences in that era is sparse, since the colonies were not settled until the early 1600's. The book divides the U.S. coast into six distinct spatial and temporal divisions: Hatteras North: 1701 – 1814; Hatteras South: 1686 – 1814; The Gulf Coast: 1722 – 1814; Hatteras North 1815 - 1870; Hatteras South: 1815 - 1870; and the Gulf Coast 1815 - 1870.

Ludlum's monograph contains local newspaper accounts of damage, reports from ships that were published in newspapers, personal letters and diaries, and historical records in archives to create descriptions and dates for the storms. As one would expect, the frequency of documented storms increases with the passing of years, as does the variety of information: later storm accounts are sometimes accompanied by more precise

scientific measurements, such as barometric pressure, wind speed and direction, and rainfall amounts. In some instances, eyewitness accounts or newspaper descriptions are detailed enough to estimate a landfall location and a lower bound on the storm's strength. Overall, it provides an early history of tropical cyclones for a portion of the North Atlantic basin (Sharkov 2000) and is a good starting place for collating historical tropical cyclone archives.

Many of the hurricanes described in Ludlum (1963) are from personal accounts or records. For example, below is an excerpt detailing the impact of the Tampa Bay hurricane of 1848. It is from a 26 September, 1848 letter written by Maj. R. D. S. Wade who was present at Ft. Brooke, near Tampa, when the storm made landfall a day earlier (See Figure 1a):

'I have to report that yesterday a very severe equinoctial storm [hurricane occurring around the time of the equinox], from the Southeast, destroyed all the wharves and most of the public buildings at this post.... The storm began about 8 A.M. from the Southeast and raged with great violence until past 4 P.M. after which it veered to the south and southwest and lulled very much toward 8 P.M. Its greatest force was from 1 to 3 P.M.... The waters rose to an unprecedented height, and the waves swept away the wharves and all the buildings that were near the Bay or river.' (Ludlum, 1963, p.154)

Some of the reports for this storm include additional meteorological observations. For example, below is a report from the post surgeon at Ft. Brooke during the 25 September, 1848, hurricane (See Figure 1b):

'The tide rose 15 feet above low water...the water commenced rising very fast at 10 A.M. and continued to rise until 2 P.M.' The surgeon also noted "the fall of the barometer from a prestorm reading of 30.12" at 0900/24th and 29.92" at 2100 to a low of 28.18" sometime prior to 1500/25th, indicative of a storm of the severest type. By 1500 the glass had recovered to 28.55" and the wind was coming out of the south.' (Ludlum, 1963, p.154)

Both of these accounts contain quantitative information about the Tampa Bay hurricane of 1848. The quantitative information takes the form of wind speeds, directions, time of occurrence, pressure, and tide heights, and is referenced to a geographic location. Our contention is that if these pieces of information are systematically arranged, they can be of substantially greater scientific value. The qualitative information present in the accounts when mapped provides visualization of

(a) Ft. Brooke (now Tampa)
Letter from Maj. R.D.S. Wade notes:
Very severe storm from the SE, destroyed all the wharves and most of the public buildings at the fort. Storm began about 0800 from the SE and raged until 1600 when winds veered to the S and SW until weakening around 2000. The storm was most intense between 1300 and 1500. Flooding was exceptionally great, no lives were lost at Ft. Brooke.

(b) Tampa

Observations from the post surgeon at Ft. Brooke: Tide rose 15 feet above low water, water rose very fast between 1000 and 1400. Barometer fell from 1020 mb at 0900/24th and 1013 mb at 2100, to 954 mb prior to 1500/25th. By 1500/25th, barometer rose to 967mb, And winds were from the S.

(c) Editor's Note:

The hurricane listed in this source as having occurred on Oct. 5, 1835 is not corroborated in any of the other historical sources. However, all of the other sources, except this one, list a hurricane in the same vicinity on Oct. 5, 1834. It is possible that the storm listed here as occurring in 1835 actually made landfall on Oct. 5, 1834.

FIGURE 1. Examples of callouts used in the HHIT. A) Example callout from the Tampa Bay Hurricane of 1848, B) Another example callout from the Tampa Bay Hurricane of 1848, C) Example of the type of information that could be found in an editor's note in the HHIT. Callouts are differentiated by color, depending on source utilized.

regional storm impacts. The information present in the accounts can be referenced to infer potential tracks, thereby permitting additional analysis.

The utility of Ludlum's monograph in support of scientific investigations is limited by a number of factors including its narrative presentations, making it difficult to visualize the storm from a synoptic perspective. This limitation has been removed by collating and mapping information contained within each narrative. This provides greater accessibility to Ludlum's quantitative information about early American storms, and provides a means to edit and update the information using additional sources.

To conduct statistical analysis on hurricane records, a list of hurricanes based on the collated historical accounts was generated. Criteria for inclusion in the collated list of U.S. hurricanes was based on several factors, including damage reports, direct meteorological observations, intensity descriptions, and swath of destruction (Figure 2). For example, here are selected excerpts from a passage in Ludlum (1963) describing a storm that would have been included in the U.S. hurricane list for 1801-1850. This example is from "The Barbados to Louisiana Hurricane of 1831":

'During the mid-August days of 1831 a tremendous hurricane, outstanding for physical size and length of destructive path, spread ruin from east of the Leeward Islands, through most of the Greater Antilles, across the Gulf of Mexico, and to the American mainland of the Mississippi Delta area. It was one of the great hurricanes of the century, or any century....At the city of New Orleans the strength of the gale was considered the greatest since that of August 1812. Small shipping along both shores of the river suffered severely, and a breach was made in the levee in the lower part of the city. The major damage in the area occurred in the northeastern section of the city when a tidal outflow from Lake Ponchartrain engulfed the lowlying parts bordering that body of water. The three day blow from the southeast had forced Gulf waters through Lake Borgne into Lake Ponchartrain where the confined waters rose to an unprecedented height.' (Ludlum, 1963, p. 140-141)

Other examples in Ludlum (1963) suggest a storm of less than hurricane strength. For example, here is an excerpt from the passage regarding "The Early Tropical Storm of 1822":

'An early season tropical storm of probably less than full hurricane intensity drove shoreward between Mobile and New Orleans on the 7th and 8th of July 1822 ... At Dauphin Island astride the mouth of Mobile Bay the surgeon weather observer at Fort Gaines noted in his weather diary: "8th-east blowing a gale; 9th-southeast gale continues; 10th-variable but more moderate"... The New Orleans press carried no reports on any local damage or effects of the storm raging to the eastward.' (Ludlum, 1963, p. 140)

Flow Chart for determination of whether a tropical cyclone reached hurricane intensity: 1800-1850

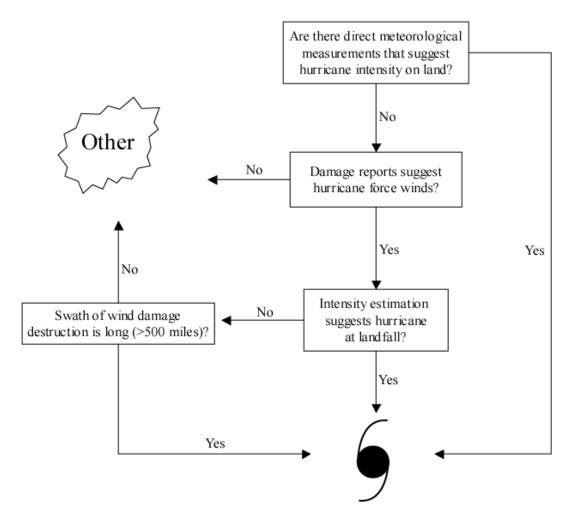


FIGURE 2. Flow chart used for determining whether a storm listed in historical tropical cyclone accounts reached hurricane intensity. If a storm is considered to have reached hurricane intensity at landfall, it is added to the collated hurricane list utilized in the statistical analysis to follow.

2.2 Additional Sources of Early U.S. hurricanes

Ludlum's work is the primary reference for early American hurricanes, but other sources of historical storm information are included. Ho (1989) provides storm summaries and track reconstructions of strong 19th century hurricanes. Barnes (1998; 2001) provides detailed accounts of Florida and North Carolina hurricanes. Sandrik (1999) provides a chronology of storms affecting northeastern Florida and Georgia. Additional unpublished sources of early 19th century hurricanes exist on the web. David Roth compiled accounts of tropical cyclone landfalls along the Texas and Louisiana coastlines. In collaboration with Hugh Cobb, David Roth has also produced a history of hurricanes in Virginia. Patrick Prokop noted hurricanes striking Savannah, Georgia; Wayne Cotterly noted hurricanes striking the coastline of Maine; and the 46th Weather Squadron based at Eglin AFB, Florida, has compiled a history of hurricanes to strike the northwestern Florida. Where appropriate, each of the sources is listed separately.

2.3 Summary of Reanalysis Project

Information about early American hurricanes is less comprehensive due to a lack of complete observational networks and reports. In an attempt to extend the instrumental record of North Atlantic hurricanes back to 1851 and improve the precision of the data record between 1871 and 1885, NOAA's Hurricane Research Division began a three year program in the year 2000 to update their HURDAT (North Atlantic Hurricane Database – also known as the "Best Track") to include tropical cyclones extending back to 1851 (Landsea 2003). Primary among their sources are the works of Ludlum and especially Fernandez-Partagas/Diaz. The NOAA project represents an effort to systematically quantify the errors associated in the historical records and add the data to the "Best-Track" database. In most cases, classification of the storm into Saffir-Simpson categories is also included. Furthermore, estimates of positional and intensity errors have been determined.

Fernandez-Partagas and Diaz (FPD) published several volumes of research on historical tropical cyclone accounts (1995/1996; 1995; 1996). These volumes cover the period from 1851 to 1900, and are the most comprehensive source of historical tropical

cyclone accounts in the North Atlantic for this period. They are far more detailed than Ludlum (1963) in terms of the number of storms documented, range of storm intensity included, and estimations of tropical cyclone tracks. FPD rely more heavily than Ludlum on ship reports, while also including standard archival accounts as well (including those written in Spanish such as Cuban observations and Spanish maritime logs). FPD generate a map depicting possible tropical cyclone tracks for each year of their research. Importantly, FPD's maps depict tracks of storms that did not make landfall. In addition, FPD found documentary evidence for far more storms than were previously thought to have occurred, due to their synthesis of a wide variety of archival materials. In many of the later accounts in FPD, early scientific measurements are included in the tropical cyclone reports. The NOAA Hurricane Reanalysis project relies heavily on the works of FPD (and Ludlum) in their reconstruction of hurricane tracks.

2.4 Proxy Tropical Cyclone Records

Evidence of early coastal hurricane activity is available from geological records. Elsner and Kara (1999) note proxy reconstruction methods of historical hurricane landfalls by analyzing pollen types in soil cores from coastal regions. The theory is that destruction of trees due to high winds causes changes in species composition, but so many other conditions can cause this effect that this technique has not yet been widely adopted for paleotempes to logy purposes. Liu and Fearn (2000a) use lake sediment records from overwash sand layers to provide a 7000-yr record of coastal changes and cata strophic hurricane landfalls (storms that were at or greater than category 4 on the Saffir-Simpson Hurricane Scale) in northwestern Florida. Where possible, overwash deposits of a known age are compared with instrumental storm data to confirm the usefulness of the technique. Similar studies were undertaken in Alabama (1993) and along the entire Gulf of Mexico coast (2000b). Although this technique has proven to be the only useful proxy in paleotempestology, the technique is not sufficiently precise to reconstruct storm events at annual or even decadal resolution (Liu et al. 2001). Therefore, proxy tropical cyclone records will not be incorporated into this research. Future extensions of the HHIT to prior centuries may incorporate such data.

The next chapter details the utilization of these historical records for creating a digital GIS tool. The tool uses ArcView GIS, and allows for the expansion, modification, and viewing of the information present in the historical sources. The tool can be accessed through the Hurricane Climate Institute at Florida State University.

CHAPTER 3

VISUALIZATION AND SPATIO-TEMPORAL ISSUES IN GIS FOR CLIMATE-RELATED APPLICATIONS

3.1 Previous research involving historical climate information

Research which involves the use of historical records for climate analysis is not new. For example, Chenoweth (1996) examined the logbooks of 227 ships during the "Year without a Summer" in 1816 and found evidence for relatively active hurricane seasons in 1815 and 1816. Garcia et al. (2001) noted changes in western Pacific typhoons based on records from the voyages of the Manila Galleons from the 16th to the 18th centuries. Furthermore, Reading (1990) conducted a reconstruction of Caribbean tropical cyclones over the last four centuries that was based on written accounts, chronologies, and published charts.

The novel feature (aside from the statistical results of the analysis) of the research presented in this dissertation is that the HHIT is the most comprehensive source of information regarding early 19th century U.S. hurricanes and it is presented in a digital format. Moreover, the information in the HHIT is created in a GIS, and there are many issues associated with the utilization of spatial data in a GIS that must be considered before making the assumption that digitally mapped information is reliable. This chapter illustrates some of these issues.

3.2 Introduction to issues in GIS

The integration of climate records over varying geographic scales and temporal resolution presents many challenges. Issues include the geographic extent of the study area, the temporal nature and duration of the research, as well as issues of display (cartographic) and issues regarding technological aspects of spatio-temporal

representation. In addition, scalar issues, selection of optimal scale, error propagation, and the use of metadata must be considered. As a Geographic Information System (GIS) is utilized in this research, much of the information presented here through other applications also pertains to their use for climate-related functions. Division into the time scales in which they occur, even though there is in reality no "gap" between these time scales, is a typical characterization of climate variability studies. Some climatic processes cannot be isolated within one time scale. Examples include the interdecadal variability of ENSO, the North Atlantic Oscillation (NAO) and its coupled mechanisms, and changes in the global carbon cycle. In climate studies, linkages across time scales are often coupled with linkages across climate-related disciplines, such as a linkage between physical aspects of climate with biological aspects (National Research Council, 1998). In all cases, an understanding of the spatial and temporal issues inherent in such data, and the linkages across time scales, is necessary for defensible analysis and representation.

An initial consideration must be given to the geographic scale to be utilized in an analysis. Cartographic definitions of scale involve the representation of the map to the representation in the real world. Consider a typical small scale topographic map from the U.S. Geological Survey at a nominal scale of 1:100,000. This 2-dimensional representation of the earth's surface is adequate for spatial features that extend linearly, such as roads, or over a region, such as a crop field. Representational issues become more complex with increasing dimensions. Most climate data extend over a region and most climatic phenomena are considered as continuous in nature. Typical examples include temperature and precipitation. Of course, if climatic data is attributed to spatial points then there will be discrete data values. However, the continuous nature of most climatic data allows for the establishment of a representational surface via interpolations of data values between spatial points. As an example of the spatial characteristics of a typical climatic variable, consider a dataset consisting of the amount of precipitation occurring over a region. For any latitude and longitude pair (location), a value of the amount of precipitation falling in that location can be determined. This would represent 2 ½ dimensional phenomena, and the most appropriate methods of analysis and display of 2 ½ dimensional data can be selected. 2 ½ dimensional data is commonly referred to as a surface, because every point on that surface has locational coordinates (usually

geographic grid for climatic research) and a single value as an attribute. However, climate data can also be represented as true 3 dimensional phenomena, which not only has X and Y locational coordinates and an associated data value, but also a Z coordinate above or below a zero point. One example of a true 3 dimensional phenomena would be mapping CO₂ in the atmosphere. Clearly then, climate data has the potential for analysis and display problems and complications related to geographic scale (Slocum 1999).

In addition to geographic scale, issues of temporal resolution must be considered when conducting climatic research. There are many conceptualizations of time; however, the GIS community is actively involved in research new definitions and models incorporating abstract temporal theories for research use. Frank (1998) partitions time into two major components, linear and cyclic. Within each of these two components of time, subdivisions of ordinal and continuous groupings are created to further the taxonomy of time. Traditionally, time in geographic research has been thought of as linear, and in most cases as time points. These time points are duration-free, and serve only as a "snapshot" of some spatial situation (Davis, as cited in Frank, 1998). Other than newer GIS models incorporating prototype temporal GIS (TGIS), GIS programs currently utilize only these linear temporal conceptions (Al-Taha and Frank, as cited in Frank, 1998) When time is defined according to fixed temporal scales such as days, months, years, and so on, these temporal scales are referred to as interval scales.

Similar to the interpolations described earlier across a spatial surface, interpolations can also be computed along a linear temporal scale. For example, a process moving along a continuous temporal scale at one spatial point allows for such interpolations. A wind speed of 50 knots at a spatial location at time A (say 8:30 AM) followed by a wind speed of 60 knots at the same point at time B (say 12 PM), allows for interpolations of both the attribute (wind speed = 55 knots) and time (10:15 PM) midway between the two temporal positions. Positional information, such as a hurricane move along a certain vector, can be interpolated between temporal and spatial locations.

A second major temporal classification is cyclical time. Many of these processes are associated with astronomic cycles, such as the tides or seasons. Cyclical time differs from the previously discussed ordinal time in that the order relation is meaningless. Cyclical time does not progress from A to B to C as in linear time; rather, it progresses

from A to B then back to A then B and so on. An understanding of these various geographic and temporal scales is necessary in order to fully grasp the multitude of issues relating to the integration of climate records over varying spatio-temporal resolutions.

3.3 Problems in climate analysis over varying scales and temporal resolutions

One of the major problems with the integration of records from different scales involves the issue of spatially aggregated data. Spatial autocorrelation refers to the tendency of for like things to occur near to one another in geographic space (Slocum 1999). An offshoot of the spatial autocorrelation tendency is the Modifiable Areal Unit Problem (MAUP) (Cao and Lam, 1997; Openshaw, 1984 as cited in Cao and Lam, 1997; Klinkenberg, WWW). The MAUP consists of two separate problems. The first, known as the scale effect, represents the variation in results when areal units are aggregated into larger and less numerous units for analysis. The aggregation problem is the variation in results that occurs due to the use of different aggregation schemes at the same spatial scales. In summary, the scale problem represents uncertainty about the number of zones to use in a study, while the aggregation problem represents uncertainty about how the data should be aggregated into the selected number of zones. The MAUP must be considered in nearly all geographic studies, as the selection of scale and data units will likely affect the desired results.

Another problem involving scale and the aggregation of data is the Ecological Fallacy problem, which can occur when generalizing from one scale to another. The ecological fallacy occurs when one makes inferences from a coarse to a fine resolution (Alker, 1969, as cited in Cao and Lam, 1997). Additionally, changing the scales of geographic analysis can also change one's interpretation of results. For example, processes that appear to be homogeneous in nature at a small scale can appear to be heterogeneous at another scale.

It is critical therefore, that the scalar unit selection be determined carefully. As climatic phenomenon occur over and on geographic space, climate data is linked with spatial issues such as the MAUP. For example, a large-scale map of a certain region may demonstrate more than adequate precipitation over a temporal period. Changing the scale may result in far different results. All data utilized in GIS has a spatio-temporal footprint.

The scale at which the data is displayed can be optimally chosen, modified by "intelligent" generalization, or changed by an abstract algorithm, however the data remain scale-dependent. Additionally, some climatic research is conducted using the earth's surface as a globe. As the globe is the only scale constant surface (Clarke, 1999), some climatic investigations (such as Global Circulation Models) require only temporal decisions and data.

Compounding these scalar problems is integrating data at different scales and or temporal resolutions. Initially one must consider the geographic scale of the available data; in order to determine optimum units for analysis, issues such as objectives of analysis and characteristics of the data must be examined (Quattrochi and Pelletier, 1991, as cited in Cao and Lam, 1997). A map depicting hurricane landfalls over a particular geographic region in the last decade integrated with a map of hurricane landfalls over the past 1000 years must be at the same geographic scale to be of analytical use if the data is to be combined. Therefore, optimum scale can be determined by the researcher based on the purpose of the investigation and the information essential for accuracy maximization, both in representation and analysis (Weibel and Dutton, 1999). Furthermore, recognition must be made regarding the accuracy of locations present in the digital maps. Changes in scale may result in less precise positional accuracy for point or line data present in the HHIT (presented in the next chapter).

Another issue one must consider in integrating spatio-temporal data is information about the data itself. "Metadata" is a term that describes the languages that are used for describing a dataset's contents, makes discovery and evaluation by a search engine easier, and allows retrieval and access of data by an end user (Goodchild, 1998). The U.S. Federal Geographic Data Committee has developed the most widely adopted set of metadata standards called the Content Standards for Digital Geospatial Metadata. The World Wide Web is dramatically changing the nature and availability of spatial data. Metadata is required in order to allow one to make decisions on the suitability of a dataset for an intended research purpose.

The metadata that will be included with the HHIT will include references to the problems inherent in the visualization of historical climate data. In the work presented in here, it is important to keep these ideas in mind. For example, estimated tracks, while

appearing to be one solid line, are in fact estimations based on a few observations that may or may not be accurate in position. As well, cities may be non-existent in the current day, or may have changed names several times since any hurricane landfalls in history.

Furthermore, issues in scale, particularly geographic scale, must be considered in relation to the propagation of errors. This is a serious matter to consider when changing scales of analysis (generalization). Curran et al. (1998) noted that errors in a particular "snapshot" of spatial data might propagate when integrated with spatial data of differing temporal composition. Small errors on a small-scale spatial analysis can become greatly magnified if the scale is increased. Consideration of error propagation must be given if scale changes are necessary between datasets. To address this problem, georeferenced cities in the HHIT are noted with small red circles; larger orange triangles represent points with greater uncertainty in their positional accuracy. The areas with the greatest uncertainty have no point indicator.

3.4 Issues involved in variable spatio-temporal data

Some situational problems exist that relate to climatic research over varying spatial and/or temporal scales. Spatial processes that occur over temporal scales are particularly applicable to discussions on representational factors. For example, sedimentation processes result in a relative sequencing from bottom to top of chronological occurrences. This is relevant to the reconstruction of historical hurricane landfalls based upon overwash deposits left by strong storms in inland water bodies (Liu and Fearn, 1993; Liu and Fearn, 2000). In this case, although scientific measurements can calculate a relative temporal occurrence of the hurricane, interval assignments such as the absolute measurements of the modern hurricane record in individual years would not apply (Frank, 1998). Therefore, pinpoint "snapshots" of the exact temporal occurrence of such storms, as are easily created for the hurricanes in the modern record, would not be readily possible. The HHIT attempts to recreate these historical "snapshots". However, it should be noted that the "snapshot" can include information from several days on one map. The temporal information presented in each HHIT map is thereby not an instantaneous spatial "snapshot" of a temporal process, but rather a temporal "snapshot" of a spatial process.

Another problem is the representation of change in spatial dataset. Interpolations of non-continuous climatic phenomenon cannot be easily created. For example, assume one wanted to determine and perform a spatial analysis on the number and tracks of hurricane landfalls along a coastline in 1995. Then assume that the only data available was for 1990 and 2000. Of course, this is just a hypothetical example, but one can see that interpolations of hurricane activity between the two data points are meaningless, especially when one considers the contigent nature of hurricane strikes. Therefore, one can only currently map and/or analyze change for existing data points when dealing with discrete data. The hurricane record in the HHIT is based on available data, and may not reflect the true number and location of hurricanes in the 1800-1850 period.

When dealing with space-time representations, two types of spatial and temporal queries can be conducted: world state and change. World state investigates the spatial distribution of a given phenomenon at a particular time. Change involves attributes that are changing for a given time scale (Puequet, 1999). As mentioned earlier, GIS systems can currently only handle "snapshot" spatio-temporal representations. Once again, the problems of complex determinations of change between "snapshots", and the inability to specifically pinpoint the temporal occurrence of a spatial phenomenon are drawbacks. To help solve these problems in general, a large effort is underway in the GIS community to develop TGIS systems (temporal GIS). Newer GIS prototypes are being designed to allow time and place to be recorded within a GIS for attribute changes. Additionally, GIS models incorporating spatio-temporal changes in entities, as opposed to locations, are under development, as are GIS models incorporating time lines as temporal vectors (Hazelton, 1991; Kelmelis and Langran, 1992, as cited in Puequet, 1999). Moreover, Stead (1998) describes an upcoming GIS model known as an object oriented approach to spatio-temporal GIS that would allow for the examination of geographic objects being moved or changed by processes over time.

3.5 Visualization of spatio-temporal data

Geo graphic visualization utilizes spatial displays to present information that is already spatial in nature. Visualization capabilities that aid knowledge discovery in large spatial databases and facilitate interactive analysis can be termed "geobrowsing". One of

the central tenets of this definition of geographic visualization is emergence, whereby features that are not explicitly created or anticipated by the viewer, are detected (Peuquet and Kraak 2002). Emergence is a feature that is present throughout the HHIT; quantitative and qualitative information linked through callout boxes to georeferenced points leads to a more lucid picture of tropical cyclone track and intensity estimations.

Time can also be considered a cartographic variable. MacEachren (1994) describes another issue in spatio-temporal representation: animation of change and/or processes. Marshall (1990, as cited in MacEachren) describes three visualization techniques used to animate simulation models of turbulence over Lake Erie. The first technique is post-processing and it involves the exploration of a simulation model with visualization tools after the model has completed a run. Tracking involves displaying a model in real-time while it is running. Finally, steering allows one to change model parameters as it is running result from visual feedback cues. Longley and Batty (1996) also discuss the simulation of space-time and the use of a prototype GIS modeling system called the Time Geographic Simulation System. (TGSS). The TGSS is an integrated modeling and GIS system that works on visual principles and allows space-time models to be generated. Furthermore, ESRI, creators of one of the most popular GIS in the world, ArcView, have developed a new GIS module that allows real-time tracking of spatio-temporal objects.

3.6 Summary of uncertainty issues in the HHIT

One must explicitly aware of some of the uncertainty issues surrounding not only the HHIT itself, but also digital geographic data in order to better understand the capabilities and limitations of GIS information. Geographic data, especially digital geographic data, is a simulation of geographic "reality"; there are too many points and variations in the earth's landscape (not to mention budget and time constraints) to perfectly represent geographic "reality" in a GIS. As mentioned earlier, most GIS schemes are static and not dynamic (Couclelis 1992), and therefore the discrepancy between geographic "reality" and geographic data can be propagated and/or amplified in a GIS project. There is a fundamental difference between uncertainty in a GIS and an actual error measurement. The uncertainty is a relative measure of the discrepancy

between geographic "reality" and the geographic data used, while the error tends to measure the value of the discrepancy (Goodchild et al. 1994). Due to the fact that the error is often not determinable (because the actual value for the feature is unknown, etc.) uncertainty is typically used to describe the accuracy of GIS projects (UCGIS 1998). There are three basic types of uncertainty that must be addressed in the HHIT. These include uncertainty in the spatial aspects of the data, the temporal properties of the data, and the quality of the data itself.

In the HHIT, spatial locations have the greatest uncertainty. While the positions of modern large cities can be accurately georeferenced, there is, in many cases, no information as to which part of the city or point location an observer was located when the tropical cyclone was recorded in the historical past. Therefore, even the most detailed information regarding early 19th century U.S. hurricanes may only be positionally accurate at the smallest scale. Although changes in scale are easily accomplished in a GIS environment, one must be aware that as the scale grows larger, so do the potential positional errors within the HHIT.

Another aspect of the uncertainty in the HHIT is the temporal properties of the data. One cannot be certain of the temporal accuracy of the information presented. It is possible that dates, days of the week, or even the time of day that information was recorded are incorrect. Furthermore, one should not assume that a layout or view in the HHIT depicts a single temporal period. For example, many maps have information from more than one day.

A third aspect of the uncertainty in the HHIT is the quality of the data presented. For example, some of the quantitative information presented in the HHIT includes wind, barometric pressure readings, temperature reading, etc. These measurements may not be directly comparable with readings in the modern time. Information on calibration of instruments, type of instrument used, or measurement techniques is very scarce, and in some cases, nonexistent. One must keep in mind the potential for large errors to be present in the quantitative, and in some cases, the qualitative data presented. As stated earlier, the metadata included with the HHIT will include a repetition of these uncertainties.

3.7 Summary

In summary, integration of differing spatial datasets in a GIS requires consideration of spatio-temporal issues. Issues of geographic data include the modifiable areal unit problem, generalization, optimum scale to use, metadata, and error propagation. Temporal issues include relative vs. absolute time, visualization of change, interpolation of change, and animation. Newer GIS models provide examples of moving beyond the standard "snapshot" view of spatio-temporal representations to a more flexible and dynamic space-time simulation. Uncertainty issues in GIS and spatial data must be considered before accepting digital maps at face value. The next chapter moves beyond theoretical issues of digital spatio-temporal visualization and uncertainty to describe the actual GIS project (HHIT) itself.

CHAPTER 4

THE HISTORICAL HURRICANE IMPACT TOOL (HHIT)

4.1 Overview

Information from Ludlum's monograph and other sources are used to construct a series of mapped accounts of tropical cyclones from the period 1800-1850, inclusive, using a Geographic Information System (GIS). The project is called the Historical Hurricane Impact Tool (HHIT).

The HHIT is organized chronologically by year. Upon opening the GIS product and selecting the HHIT directory, a listing of years between 1800 and 1850 appears, appended by the suffix *.apr (Figure 3). This suffix identifies the file as a GIS project. For any year selected, the tropical cyclones are organized chronologically by landfall date, with the first storm of the season listed as storm one.

4.2 Callouts

Descriptive information regarding hurricanes and tropical storms was obtained from hurricane historiography and input as callout boxes over base maps of the United States. The majority of callouts contain information as described in sources such as Ludlum (1963), with only some basic paraphrasing to make the descriptions more compact. For example, Figure 1 (previous chapter) depicts callout boxes based on information from the 25 September, 1848, Tampa Bay hurricane. The top callout contains information from the letter of Maj. R.D.S. Wade and the middle callout contains observations from the post surgeon at Ft. Brooke. The Ludlum callout boxes are shaded in yellow to distinguish them from the background. The boxes are positioned on the map near the location described within and include a pointer to the location, if known.

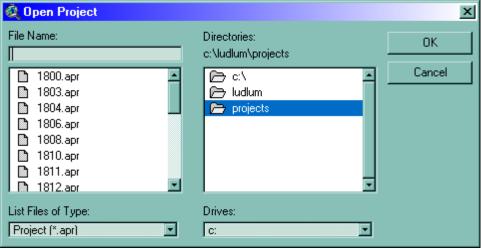


FIGURE 3. GIS project selection dialog box. The GIS Tool is designed so that each year in which a hurricane made a U.S. landfall is a separate GIS project (projects end in *.apr). The HHIT is chronologically organized.

Instances in which the precise location is unknown utilize a text box rather than a callout. The text boxes are scale-dependent: changing the map scale changes the text scale in reciprocity. The background color in the callout boxes depends on the historical source. Table 2 lists the sources and their associated background color.

In situations in which information was added to the descriptive callouts, a separate callout box, under the title "Editor's note," is used. For instance, consider an example in which a storm listed in one source on a particular date appears to have been a storm listed in several other sources on a different date. The callout used to describe this situation is shown as the bottom callout in Figure 1. The descriptive layouts for each storm (in other words, the view of each storm prepared for hard copy) includes a summary for each storm listed in Ludlum (1963). These summaries include statements taken directly from the descriptive accounts with some paraphrasing for clarity. In general, statements made by the editor and not garnered from Ludlum (1963) are included in separate callout boxes, as listed above. The callout boxes provide georeferenced descriptions of the information in the historiographies. They allow greater accessibility to the information and provide a mechanism for combining additional information in a digital environment.

4.3 ArcView GIS

The HHIT utilizes Environmental Systems Research Institute's (ESRI) ArcView GIS software. The original version used to create the project is version 3.1. Therefore, users of the project must have ArcView 3.1 or later installed on their system, or the newer ArcGIS software. The project was designed utilizing the Windows OS. Testing for cross-platform capability has not been performed. The HHIT has been designed to incorporate all necessary shapefiles and GIS projects onto portable media such as CD-ROM. Once the GIS software has been installed on the users computer, the project shapefiles (the files used by the GIS to display the hurricane information) must be installed to the users hard disk (in most cases, the C: drive). To view any project, open the GIS and select "Open Project", and navigate to the directory containing the GIS projects (included with any copy of the HHIT). A menu box will open. The GIS projects are arranged by year (Figure 3).

TABLE 2. Source and color used in callout boxes throughout GIS project.

Tilber 20 source with total word in this will the brought of single brought			
Source	Color Utilized		
Ludlum	Light Yellow		
Roth (Roth and Cobb)	Light Blue		
Но	Moss Green		
Barnes	Light Red		
Dunn and Miller	Light Purple		
Cotterly	Lime Green		
Prokop	Blue-Green		
46 th Weather Squadron	Light Magenta		
Sandrik	Peach		
Editor's Note	Light Green		

Upon selection, the project opens and the GIS displays the various menu icons available to the user. The two most commonly used menu icons are the "Views" and the "Layouts". The "Views" are the core of each project, and contain the descriptive information relating to each storm (Figure 4). The "Views" also contain the estimated tracks of each storm. Again, they are organized by the day of the season in which a tropical cyclone affected the U.S. coastline. The "Layouts" are designed as hardcopy layout tools (Figure 5). This is where a user will find finished descriptive maps, track maps, intensity estimations, and further storm descriptions. The "Views" and the "Layouts" can be sized by positioning the cursor over the corner of the "View" and while clicking the left-hand mouse button, drag and drop the corner at the appropriate size. Alternatively, the minimize and maximize functions may be used to size the "Views" and the "Layouts".

Within the "Views" are callout descriptions for each storm. Upon opening a "View", the user sees a map display containing descriptive information for each storm and a selection of "Themes" from which to choose (Figure 6). Individual historical sources are treated as separate "Themes" for each storm. The "Themes" can be toggled on and off through a checkbox, located in the upper left-hand corner of each theme. Each "Theme" represents the storm description from an individual historical source. In some instances, the amount of descriptive information from a single source is limited; in these cases, sources are grouped together under one "Theme" titled "Other Sources". The "Views" involving tracks have one "Theme" titled "Track". Toggling the checkbox for this "Theme" will alternately display and hide from view the track of the storm. Where no track is specified, "Track Unspecified" will appear in the "View".

Within "Themes", storm impacts in the United States and to vessels in adjacent coastal waters are manually input on a base map using the callout boxes. Descriptive information such as damage reports, meteorological observations, and ship reports are included. Storms are listed chronologically by year. Additional value is added to the maps with the inclusion of a possible storm track. These tracks are available for viewing and modification in the "View" options and available for examination in the "Layout" as well. Estimated storm intensities at landfall are also included, but are present only in the "Layout" for each storm. The descriptive layout for the Tampa Bay hurricane of 1848 is



FIGURE 4. View selection screen. The Views are organized by day of the year in which they affected the U.S. coast. The black line is a highlight used to select which view to open.

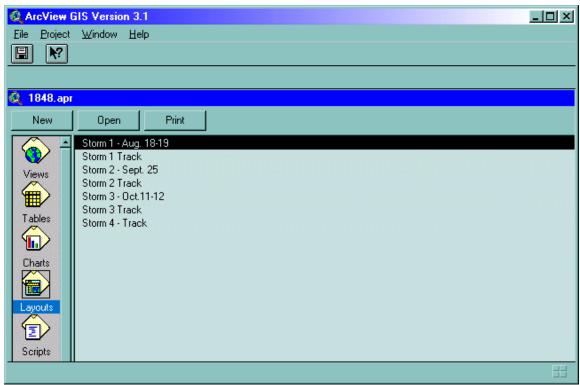


FIGURE 5. Layout selection screen. The Layouts are organized similarly to the views, except that only descriptions based on Ludlum (1963) are included. All storms have track layouts.

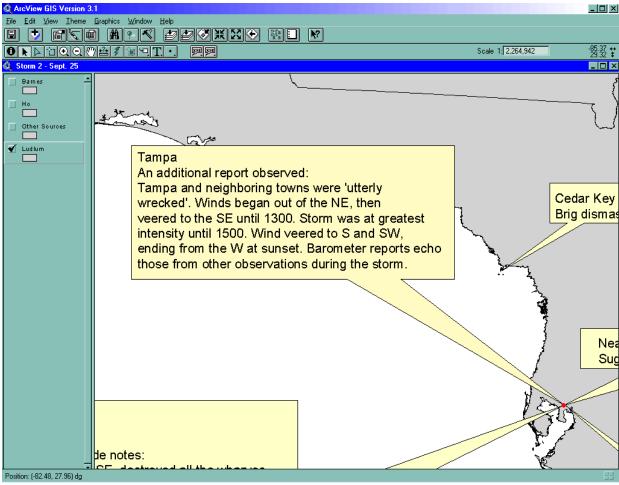


FIGURE 6. Sample theme callout. Once a "View" for a particular storm is opened, a list of "Themes" is available in the left margin. Each theme can be toggled on and off via a checkbox in the upper left-hand corner. Each theme represents descriptive information about each tropical cyclone from a particular historical source (see text for explanation of "Other Sources").

shown in Figure 7. Note the textual storm summary: this item culls information from Ludlum, and in some cases the editor, into an overall summary of the storm's track and effects.

Because the HHIT is digital, editing and modification are possible. For example, new documentary accounts can be added to the existing tropical cyclones in the tool by adding a new "Theme". Entirely new storms can be added by creating a new "View". Additional years can be added by creating new projects with separate views for each storm. One such editing task would be the determination of a possible storm track.

Since empirical measurements are sparse, the historical storm evidence comes largely from diary entries, newspaper summaries, and personal correspondence. The potential for larger errors in track location and storm intensity is high. However, a preponderance of evidence can lead to a more definitive estimation of track and/or intensity for some well-documented cases. For most storms, however, track and intensity estimates can be considered baseline approximations between confidence bounds. While these are not depicted for the tracks themselves, the intensity estimations provided in the current version of HHIT should be considered as ± 1 Saffir-Simpson Category.

Three types of tracks are given in the HHIT. Those that are taken directly from Ho (1989) [Tannehill 1956] are colored blue [green]. Those that are based on our analysis are colored red. Where estimates are possible, tracks are modified from solid to dotted lines to indicate weakening to tropical storm strength. A sample track map for the Tampa Bay hurricane of 1848, is shown in Fig. 8. The blue track is taken directly from Ho. Our estimated track is shown in red.

4.4 Accessing HHIT

As an ArcView GIS series of projects, the HHIT is accessed through the installation of the necessary shapefiles and GIS projects (.apr) on the client's computer. Currently, these projects and shapefiles are available through the Hurricane Climate Institute at Florida State University on request via CD-ROM. The GIS files must be installed in the appropriate directory in order to have viewing and editing capability. The advantages of the physical installation of the files is that the GIS projects can be updated with new information, modified to contain additional applications, or edited to correct

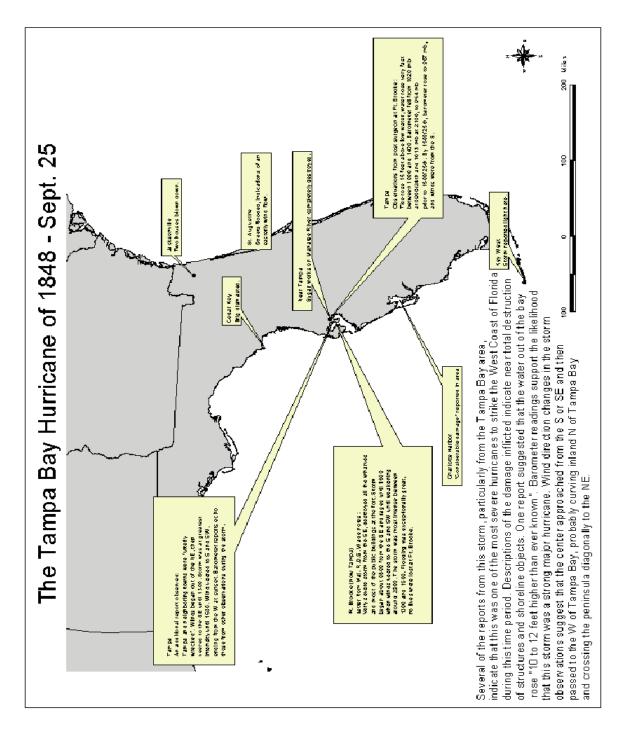


FIGURE 7. Sample descriptive layout for the Tampa Bay Hurricane of September, 1848. The callouts, as well as descriptive summary, are from Ludlum (1963).

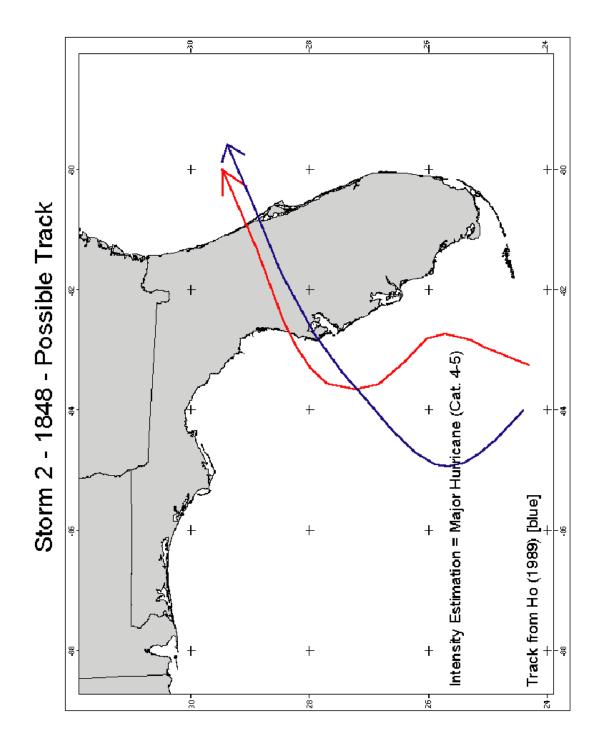


FIGURE 8. Sample track and intensity estimation for the Tampa Bay Hurricane of September 26, 1848. The track in red are based on our analysis. Intensity estimations are subject to a \pm 1 Saffir-Simpson category error margin.

any mistakes. In the near future, it is anticipated that the GIS projects in the HHIT will be made available via the internet utilizing ESRI's Arc IMS. This will allow for more rapid access to the data present in the HHIT, but will restrict the use of the data to viewing only. The link to the online HHIT will be made available on the website of the Hurricane Climate Institute at Florida State University when completed.

The next chapter details trends in U.S. hurricanes based on statistical analysis of the data present in the HHIT. A table listing all of the tropical cyclones in the HHIT is included, as well as analysis of both the entire coastline and regional landfalls.

CHAPTER 5

HURRICANE CLIMATOLOGY

5.1 Tropical Cyclones in the HHIT

The HHIT includes evidence from 90 tropical cyclones during the 51-year period. Of these, 56 are considered to have hit the United States at hurricane intensity (>73 mph) and 24 at major hurricane intensity (>110 mph). The most active year was 1837 with 10 tropical cyclones, 6 of which made landfall along the U.S. coast. The second most active year was 1844, with 8 tropical cyclones and 4 landfalls. Thirty-seven of the 51 years had evidence of at least one tropical cyclone. The exceptions were 1801, 1802, 1805, 1807, 1809, 1823, 1826, 1828, 1832, 1833, 1836, 1838, 1845, and 1847.

Table 3 lists the tropical cyclones evident in the HHIT. The table lists the basic storm information including year, date of initial landfall, storm name, and estimated intensity. In addition, the estimated landfall location is listed, with separate intensity estimates for tropical cyclones that made landfall more than once. There are a handful of tropical cyclones that were recorded as making landfall more than once in the 1800-1850 period (6). Only one of these tropical cyclones was associated with a second landfall at hurricane intensity (1850, Storm 2, Aug. 23/25).

5.2 Seasonal Activity

Descriptive statistical analyzes can be performed on the hurricane information assembled in HHIT. The HHIT includes chronological listings of tropical cyclones by year and provides estimated landfall dates for each tropical cyclone to strike the U.S.

TABLE 3. List of Tropical Cyclones in the HHIT. Major refers to category 3 or higher on the Saffir-Simpon scale. Estimated landfall location and affir-Simpson category at landfall (est.) are included. See Table 2 for a listing of sources. Initial given is first initial of source name.

given is first initial of source name.						
Year Date	Storm	Major	Region	Land fall Location (est.)	Storm/Source	
1800 August ??	Storm 1	No	G	New Orleans, LA (1)	R	
1800 Oct. 4	Storm 2	Maybe	E	Charleston, SC (2-3)	L	
1803 Unknown	Storm 1	No	E	New Bern, NC (1)	В	
1803 Aug. 29	Storm 2	No		Offshore – NC (1)	R	
1804 Sept. 6	Storm 1	Yes	E	GA/SC (3)	L,R,D+M,S	
1804 Oct. 9	Storm 2	Maybe	E	NJ (2-3)	L, R, D+M	
1806 Aug. 22	Storm 1	Yes	E	NC (2-3)	L, R	
1806 Sept. 16	Storm 2	No	F	FL (1)	S	
1806 Sept. 28	Storm 3	No	E	NC/VA (1)	R	
1808 Sept. 12	Storm 1			Unknown - VA/MD (TS)	R	
1810 Sept. 12	Storm 1		E	SC (TS)	L	
1811 Sept. 10	Storm 1	No	Е	SC (1)	L, D+M	
1811 Oct. 5	Storm 2	Maybe	F	FL (2-3)	S	
1812 Aug. 19	Storm 1	Yes	G	LA (3)	L, R	
1812 Oct. 1/5	Storm 2	No	F	FL (1-2)	S, D+M	
1813 Aug. 28	Storm 1	Yes	Е	SC (3)	L, R, D+M, S	
1813 Sept. 16	Storm 2	Yes	F	FL (3)	S	
1814 Jul. 1	Storm 1	No	Е	SC (1)	D+M	
1815 Sept. 3	Storm 1	Yes	Е	NC (3-4)	L, B	
1815 Sept. 23	Storm 2	Yes	Е	NY/CT (3-4)	L, H, D+M, C	
1815 Sept. 28	Storm 3			Offshore - SC (TS)	D+M	
1815 Oct. 24	Storm 4	No		Offshore - VA (1)	R	
1816 Sept. 18	Storm 1		E	VA (TS)	R	
1817 Aug. 7	Storm 1	No	F; E	1-FL/GA (1) 2-SC/NC (TS)	S	
1818 Sept. 12	Storm 1	Maybe	G	TX (2-3)	L, R	
1819 Jul. 27	Storm 1	Yes	G	LA/MS (3-4)	L, WX, R	
1819 Sept. ??	Storm 2		G	Gulfcoast (TS)	В	
1820 Sept. 13	Storm 1	No	E	SC/NC (1-2)	L	
1821 Sept. 3	Storm 1	Yes	E; E	1-NC/VA (4-5) 2-NJ/NY (TS)	L,B,H,D+M,R	
1821 Sept. 15	Storm 2	Yes	G	MS (3)	L,B,R,WX	
1822 Jul. 8	Storm 1		G	MS (TS)	L	
1822 August ??	Storm 2	No		Offshore - NC (1)	D+M	
1822 Sept. 27	Storm 3	Maybe	Е	SC (2-3)	L, D+M, R	
1824 Sept. 14	Storm 1	Yes	Е	GA (3-4)	L,B,D+M,PR,S	
1825 Jun. 2	Storm 1	No	F	FL (1-2)	S	
1825 Oct. 2	Storm 2	No	F	FL (1)	S	

TABLE 3. - CONTINUED

TABLE 5 CONTINUED					
1827 Jul. 30	Storm 1	No		Offshore - NC (1)	D+M
1827 Aug. 25	Storm 2	Yes	E; E	1-NC (3-4) 2-MA (TS)	L,B,D+M,R
1829 Aug. 26	Storm 1		E	VA (TS)	R
1829 Sept. 10	Storm 2	No	G	TX (1-2)	R
1830 Aug. 15	Storm 1	Maybe	E	NC (2-3)	L,B,D+M,S,R
1830 Aug. 24	Storm 2	No		Offshore - NE (1)	L, B
1830 Oct. 6	Storm 3	No		Offshore - Mid. Atl. (1)	L
1831 Jun. 10	Storm 1		F	FL (TS)	D+M,S
1831 Aug. 17	Storm 2	Yes	G	LA (3-4)	L,B,R
1831 Aug. 28	Storm 3		G	LA (TS)	L, R
1834 Sept. 4	Storm 1	No	E	NC (1)	L, R
1835 Aug. 18	Storm 1	Yes	G	TX (3)	L, R
1835 Sept. 15	Storm 2	Yes	F	FL (3)	L,B,S
1837 Aug. 1	Storm 1	No	F	FL (1)	L,D+M,S
1837 Aug. 7	Storm 2	No	F	FL (2)	L,B, W X
1837 Aug. 6	Storm 3	Maybe	F	FL/GA (2-3)	L, D+M, S
1837 Aug. 18	Storm 4	No		Offshore - SE coast (1)	L,B,R,S
1837 Mid-Aug.	Storm 5	No	F	FL (1)	В
1837 Aug. 30	Storm 6	Yes	F	FL (3)	L,B,D+M,S
1837 Sept. 13	Storm 7		F	FL (TS)	L
1837 Sept. 26	Storm 8		F	FL (TS)	L,S
1837 Oct. 1	Storm 9	Yes	G	1-TX*(Strafe) 2-LA (4-5)	L,R,B,D+M,WX
1837 Oct. 29	Storm 10			Offshore - NC (TS)	L,B
1839 Aug. 28	Storm 1	No		Offshore (2)	L,R
1839 Sept. 15	Storm 2		G	LA (TS)	R
1839 Nov. 5	Storm 3	No	G	TX (1)	R
1840 Jun. 19	Storm 1		G	TX/LA (TS)	R
1841 Sept. 14	Storm 1		F	FL (TS)	L,B
1841 Oct. 3	Storm 2	Maybe		Offshore (2-3)	L, D+M, R
1841 Oct. 18	Storm 3	No		Offshore - FL (1)	L,B
1842 Jul. 13	Storm 1	Yes	E	NC/VA (3-4)	L,B,D+M
1842 Aug. 2	Storm 2			Offshore (TS)	S
1842 Aug. 24	Storm 3	No	E	NC (1)	D+M,B
1842 Sept. 8	Storm 4	No	G	TX (1-2)	L, B
1842 Sept. 17	Storm 5		G	TX (TS)	L,R
1842 Sept. 22	Storm 6		F	FL (TS)	L,B
1842 Oct. 4	Storm 7	Yes	F	FL (3)	L,H,B,S,R,D+M
1842 Oct. 26	Storm 8			Offshore- FL (TS)	L,S
1843 Sept. 13	Storm 1	Yes	F	FL (3-4)	L,B,D+M,WX
1844 Jun. 12	Storm 1		G	LA (TS)	R
1844 Aug. 4	Storm 2	Yes	G	TX (3)	L,R
1844 Sept. 8	Storm 3	No	F	FL (1)	L,H,B,S

TABLE 3. - CONTINUED

1844 Oct. 3	Storm 4	No		Offshore (2)	L,B, D+M
1846 Sept. 8	Storm 1	Yes		Offshore - NC (3-4)	L,B
1846 Oct. 11	Storm 2	Yes	F	FL (4-5)	L,H,B,S,D+M
1848 Aug. 18	Storm 1		G	LA (TS)	L
1848 Sept. 25	Storm 2	Yes	F	FL (4-5)	L,H,B,D+M,S
1848 Oct. 11	Storm 3	Yes	F	FL (3)	L,B,D+M,S
1848 Oct. 17	Storm 4	No	G	TX (1-2)	R
1849 Sept. 13	Storm 1	No	G	TX (1)	L
1849 Oct. 6	Storm 2	No	E	MA (1)	L
1850 Jul. 18	Storm 1	No	E	NC (1-2)	L, R
1850 Aug. 23/25	Storm 2	Maybe	F	1-FL (2-3) 2-NY/CT (1)	L,B,D+M,R
1850 Sept. 8	Storm 3	No		Offshore (1)	L

coast; these dates are listed in the storm's "View". Comparisons are made between the number of U.S. hurricanes in 50-year epochs (1800-49, 1850-99, 1900-49, 1950-99). There are 54 hurricanes in the period 1800-49. This compares with 89 known landfalls in the period 1850-99, with 90 in the period 1900-49, and with 75 in the period 1950-99 (Table 4). The earliest epoch contains the lowest number of landfalls. This is likely the result of undetected storms introducing a temporal bias in the overall record. However, natural variability is quite large as evidenced by a 17% reduction in the number of landfalls between the first and second halves of the 20th century. Therefore, it is not easy to tell what portion of the reduction is due to missing storms and how much is due to natural variability.

Questions about the most likely period of activity within a season are also determined. These comparisons are less affected by the bias of fewer early epoch storms assuming the probability of not detecting a storm is independent of the time of year. For each of the four epochs, I have counted the number of landfalls using 19 consecutive 10-day bins, beginning with June 1. Figure 9 is a set of bar plots. The hurricane season begins in June and peaks in September. Fewer storms are noted by mid-October with the season ending during November. The season onset appears more gradual than its termination producing a skewness in the distribution of landfall counts. The sample coefficient of skewness (y) calculated using the method of Fisher is:

$$\gamma = \left[\frac{\sqrt{n(n-1)}}{n-2}\right] \frac{\frac{1}{n} \sum \left(x-\pi\right)^{n}}{\left[\frac{1}{n} \sum \left(x-\overline{x}\right)^{2}\right]^{\frac{1}{3}}} \tag{1}$$

where n is the total number of storms.

The greatest skewness is noted in the earliest interval with a value of -0.879. For the other periods, skewness values are -0.741 for the period 1850-99, -0.211 for the period 1900-49, and -0.441 for the period 1950-99. The negative values indicate there are more storms after the mean date than before, and this is true regardless of the epoch. The hurricane season mean date is 6 September in the 1800-49 data, 5 September in the 1850-

TABLE 4. Summary statistics of seasonal U.S. hurricane activity. Note that the "Best Track" data extends back to 1851.

Period	No. Years	No. Hurricanes	Mean Date	Median Date	Coefficient of Skewness	Mode Interval
1800- 1849	50	51	Sept. 6	Sept. 10	-0.879	Sept. 8-17
1850- 1899	50	89	Sept. 5	Sept. 10	-0.741	Sept. 8-17
1900- 1949	50	90	Sept. 1	Sept. 4	-0.211	Sept. 8-17
1949 1950- 1999	50	75	Sept. 2	Sept. 7	-0.441	Sept. 1-7, Sept. 8-17

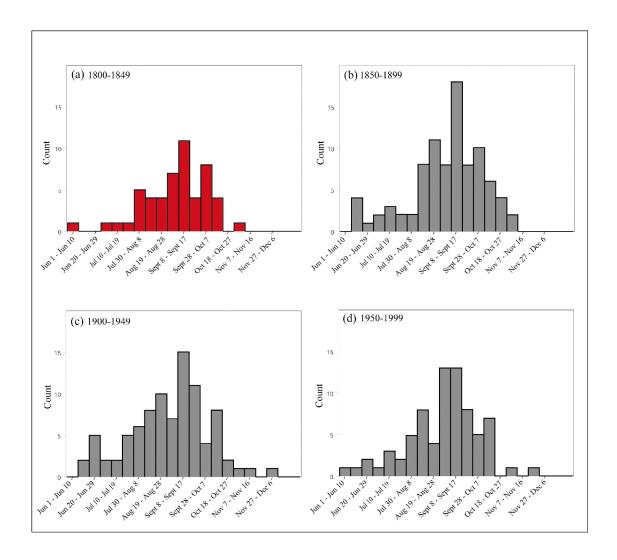


FIGURE 9. Seasonal climatology of U.S. hurricane landfalls. The hurricance season is grouped into 10-day bins and the Y-axis represents landfall counts. The information gained through the collation of historical hurricane accounts for this project is depicted in red.

99 data, 1 September in the 1900-49 data, and 2 September in the 1950-99 data. The hurricane season median date is 10 September in the 1800-49 and 1850-99 hurricane data, 4 September in the 1900-1949 data (rounded up from halfway through 3 September), and 7 September in the 1950-1999 data. The means and medians cluster in time during the first 10 days of September. Figure 10 shows the cumulative probability curves. The probability curves are similar between epochs.

The distributions appear to be robust over the entire period of record, with the greatest threat of a U.S. hurricane occurring during the days between 8 September and 17 September. To compare the distributions statistically, I utilized a Kolmogorov-Smirnov Goodness-of-Fit Test (K-S GOF test). This statistic is used as an alternative to the chisquare GOF test for testing the similarity between two frequency distributions. Although the K-S GOF test technically requires continuous data, only very small errors are created when using discrete data, and the technique is often applied to distributions consisting of discrete data. In the utilization of the Kolmogorov-Smirnov GOF test, the observed distribution is compared with a particular expected distribution, such as the normal distribution. The null hypothesis is that there is no significant difference between the distributions (McGrew, Jr. and Monroe 2000). The 1800-1849 distribution was compared with the 1850-1899 using the K-S GOF test, and the result (p-value = 0.3057) demonstrates that the two distributions are similar (there is not enough evidence to reject the null hypothesis). Similar procedures were performed for the 1800-1849 and 1900-1949 (p-value = 0.3057) and the 1800-1849 and 1950-1999 (p-value = 0.9781) distributions. The results show that the shape of the distribution of the seasonal hurricane landfall activity for the 1800-1849 period does not differ significantly from the distributions from the 1850-1999 period. This provides some confidence in the historical documents of Ludlum and others. For instance, the seasonal distributions suggest that it is unlikely that the documents contain information about extratropical systems. If such systems were included, one would expect the distribution during the early half of the 19th century to be somewhat different from the other epochs.

The monthly distribution of U.S. hurricane landfalls was also examined. Figure 11 depicts the monthly landfall distribution for each of the four 50-year periods. While

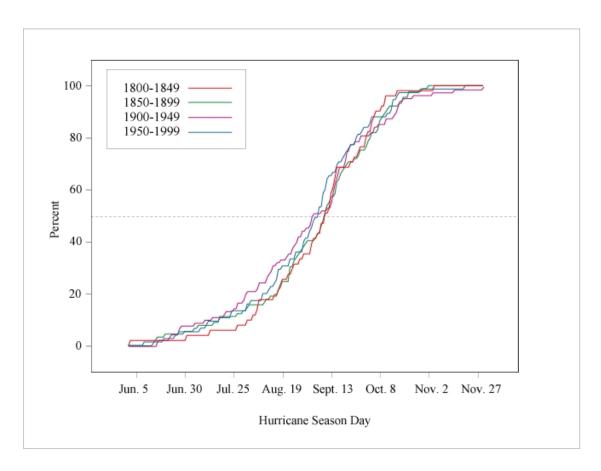


FIGURE 10. Seasonal climatology of U.S. hurricane landfalls. The figure depicts four 50-year cumulative distribution functions based on the daily landfall records during hurricane season.

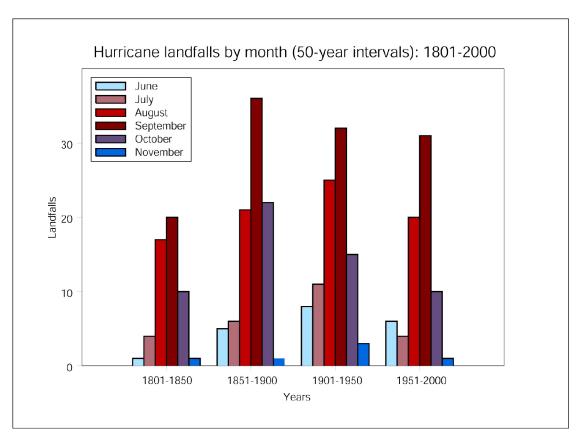


FIGURE 11. Monthly Distribution of U.S. hurricane landfalls, by period, 1801-2000.

the number of landfalls is different for each of the periods (as discussed earlier in this section), the monthly distribution has remained relatively constant. For instance, in all periods the season builds slowly until August, when landfall activity begins to pick up. September represents the peak of hurricane activity for all of the 50-year periods, with the activity moderating by October, and ceasing rapidly in November.

5.3 Annual Activity

Figures 12 and 13 depict total and major U.S. hurricanes in each of the four 50-year periods utilized throughout this paper. Figure 12 demonstrates that the greatest number of landfalls in one year was 7 in 1886 and 1985. Many years exhibited no landfalls, but the majority of years experienced at least one landfall. Figure 13 depicts the major hurricanes to strike the U.S., by period. The maximum number of major hurricanes to strike the coast between 1801 and 2000 was 3, which occurred in 1879, 1893, 1909, 1933, 1953, and 1985.

Table 5 notes the summary statistics for all U.S. hurricanes for four 50-year periods from 1801-2000. The most active period in terms of total U.S. hurricanes was 1851-1900, when there were 96 land falls. The least number of reported landfalls was in the 1801-1850 period with 55. Table 4 also lists the number of major hurricane landfalls by period, with 1901-2000 (1801-1850) being the most (least) active in terms of major U.S. hurricanes with 37 (23) reported landfalls.

Table 6 lists the average number of total and major hurricane landfalls per year, by period. Based on the table results, an average year during the 1851-1900 period ended with approximately two hurricane landfalls, while the average for 1801-1850 was just slightly over 1 landfall per year. The period with the greatest risk of a major hurricane making landfall in any year was 1901-1950, with an average of 3 major hurricane landfalls in 4 years. The period with the least risk from major hurricanes was 1801-1850 with an average of approximately 1 landfall every two years.

Figure 14 notes the annual occurrence of landfalls for each of the four 50-year non-overlapping epochs. The figure describes the number of years experiencing 0,1,2,3, or 4 hurricane landfalls. Changes in the frequency distribution are evident between

TABLE 5: Summary Statistics for U.S. total and major hurricanes, by period.

Period	Total U.S. Landfalls	Major U.S. Hurricanes
1801-1850	55	24
1851-1900	96	27
1901-1950	94	37
1951-2000	80	31

TABLE 6: Annual averages for U.S. total and major hurricanes, by period.

Period	Total U.S. Landfalls	Major U.S. Hurricanes
1 CHOU	Total C.S. Landians	Major 0.5. Trufficancs
1801-1850	1.10	0.46
1851-1900	1.92	0.54
1901-1950	1.88	0.74
1951-2000	1.60	0.62

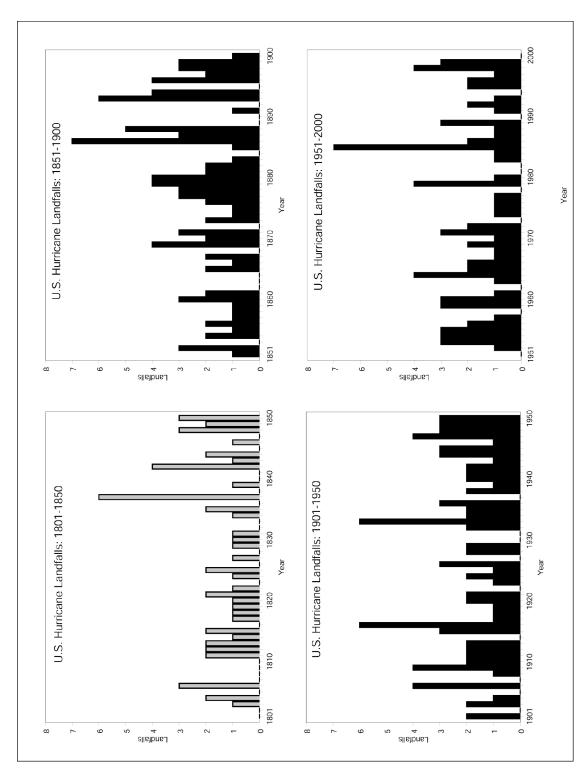


FIGURE 12. U.S. Total Hurricane Landfalls, by period, 1801-2000.

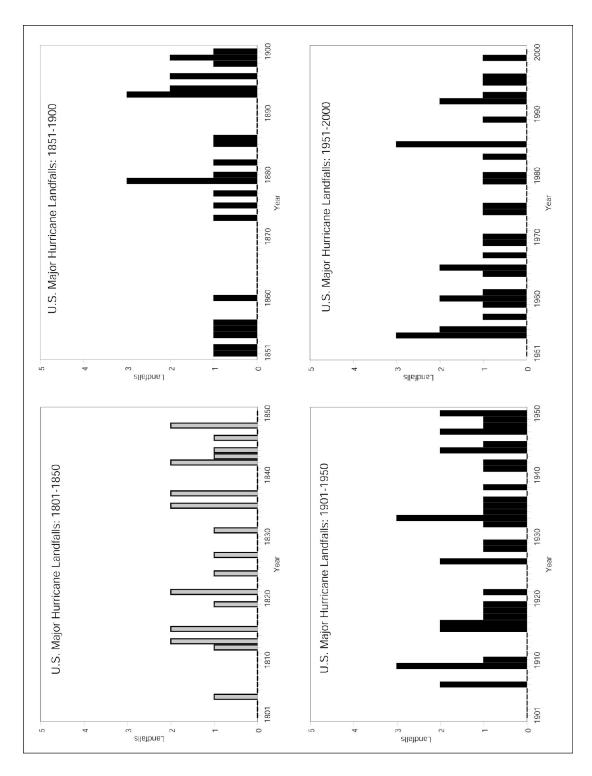


FIGURE 13. U.S. Major Hurricane Landfalk, by period, 1801-2000.

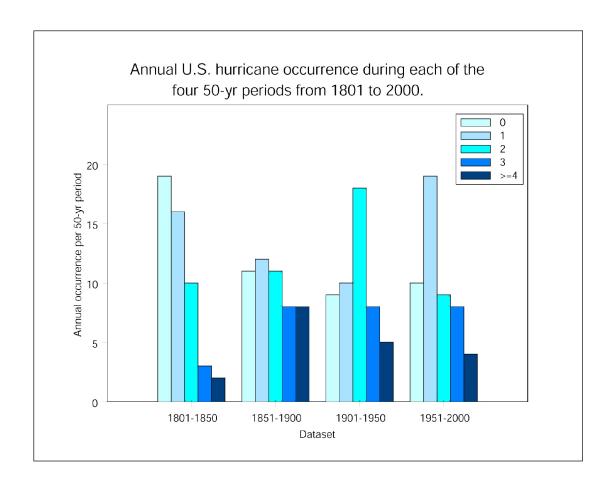


FIGURE 14. Annual occurrence of U.S. hurricanes for four 50-yr non-overlapping epochs between 1801-2000.

epochs. Especially noteworthy is the positively skewed nature of the occurrence distribution in the first epoch.

Figure 15 depicts the numbers of total and major U.S. hurricane landfalls by period. As is evident in the figure, the 1801-1850 period possesses the least number of reported landfalls. One likely explanation for the low number of landfalls is that much of the coastline along the Gulf states and Florida had very little population at this time. In fact, the metadata for the NOAA reanalysis project notes this likelihood in its project documentation. The authors note that the following regions were likely too underpopulated for accurate storm counts before the indicated year: Texas - south: 1880; Texas - central: <1851; Texas - north: 1860; Louisiana: 1880; Mississippi: <1851; Alabama: <1851; Florida - northwest: 1880; Florida - southwest: 1900; Florida - southeast: 1900; Florida - northeast: 1880.

Their definition of "settled region" for these estimates is two inhabitants per square mile, and the population statistics are based on U.S. Census data and other historical analysis. Therefore, the accuracy of the early 19th century hurricane data is likely directly tied to the number of inhabitants along the U.S. coastline throughout that period. In support of this theory, it would follow that if the population was limited along the coastline then perhaps stronger storms would have been noted, and weaker storms may have been less so. However, even the stronger storms are not likely to have been sampled at their maximum intensity. Therefore, in addition to the bias in the number of storms present in the collated hurricane list, there exists a bias in the storm intensity. Figure 15 also notes the ratio of total (major) hurricanes recorded in each period to the sum-total (total) number of hurricanes for all (in each) periods (period). The highest ratio of major hurricane to total hurricane landfalls in each period occurs in the 1801-1850 period. This provides some evidence that perhaps the strongest storms were noted in the 1800-1850 epoch, while weaker storms may have gone unrecorded.

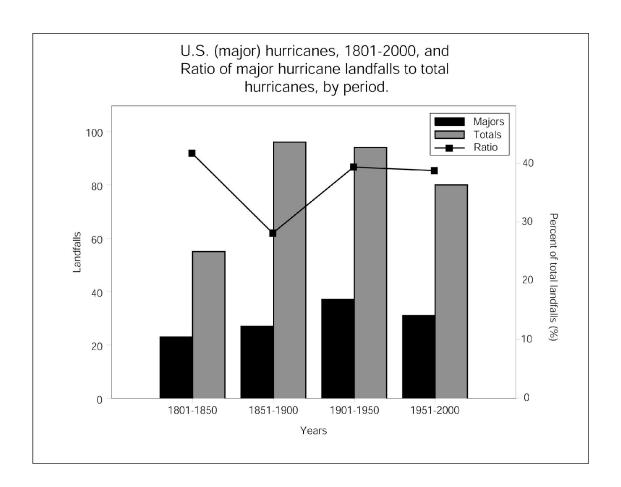


FIGURE 15. U.S. Major and Total Hurricane Landfalls, by period, 1801-2000 and the Ratio of U.S. total (major) hurricane landfalls to sum-total (total) landfalls in all (each) periods (period).

5.4 Regional Activity

The U.S. coastline was divided into three regions in order to better understand climatic influences on hurricane landfalls. The Gulf coast region comprises the U.S. Gulf coast from Texas to Alabama. Florida is considered a separate region, and the U.S. coast line from Georgia through Maine is called the East coast region. Table 7 presents the summary statistics for each of these three regions from 1801-2000. The Gulf coast and Florida receive the bulk of U.S. hurricane landfalls, but in both 1801-1850 and 1951-2000, the East coast received more landfalls than Florida. The annual average statistics in Table 7 demonstrate that the annual average for hurricane landfalls in Florida during the most recent temporal period (1951-2000) is much closer to that in the earliest period (1801-1850) than in the preceding 100 years (1851-1950).

Figure 16 details the regional landfalls over the last 200 years. Due to the fact that most years experience only one or zero landfalls, the figure has been designed to emphasize periods of extraordinary activity. In the Gulf coast region, the most active year was 1886, with 4 landfalls. In Florida, 5 hurricanes made landfall in 1837; this represents the greatest number of landfalls in any one region between 1801 and 2000. The East coast experienced three years with 3 landfalls; 1893, 1954, and 1955.

The ratio of landfalls in each region to the total number of landfalls for each period was also noted. Figure 17 details the ratios for each of the three regions for the four 50-year periods. Of note is that fact that in the first and third periods, the Gulf coast and the East coast appear to have inverse relationships, whereas in the second and last periods, the ratios are much more similar. Also of note is that Florida demonstrates an inverse relationship with the East coast across all time periods: when there is a high ratio of landfalls in Florida, there is a lower ratio of landfalls in the East coast region, and vice versa.

This chapter detailed some descriptive statistics of U.S. hurricane activity from the first half of the 19th century and compared them to statistics of U.S. hurricanes from the late 19th through the 20th century. The following chapter examined climatic influences on U.S. hurricanes. In particular, the NAO, ENSO, and the PDO are

investigated for their impact on hurricane frequency and location. Additional investigations of sunspot and volcanic activity are included.

TABLE 7: Summary statistics and averages for U.S. hurricanes by region.

Period	Gulf	Florida	East	Gulf	Florida	East
	Total	Total	Total	Average	Average	Average
1801-1850	14	18	23	0.28	0.36	0.46
1851-1900	32	34	30	0.64	0.68	0.60
1901-1950	39	36	19	0.78	0.72	0.38
1951-2000	30	22	28	0.60	0.44	0.56

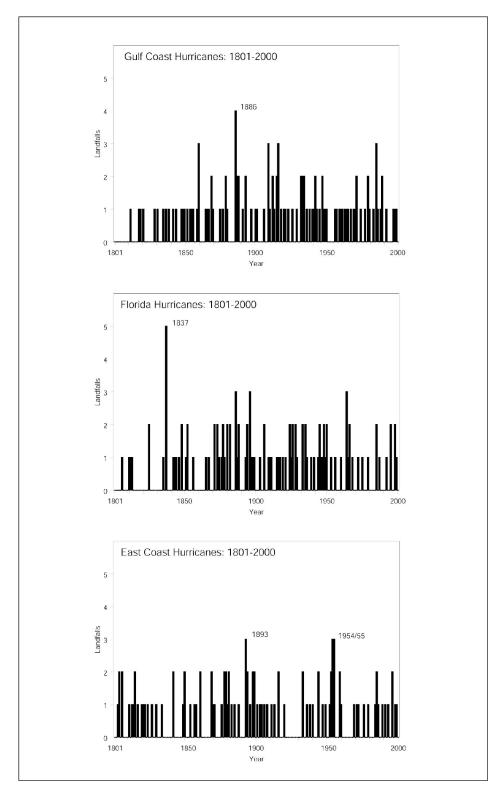


FIGURE 16. Regional U.S. hurricane landfalls, by period. Most active year noted.

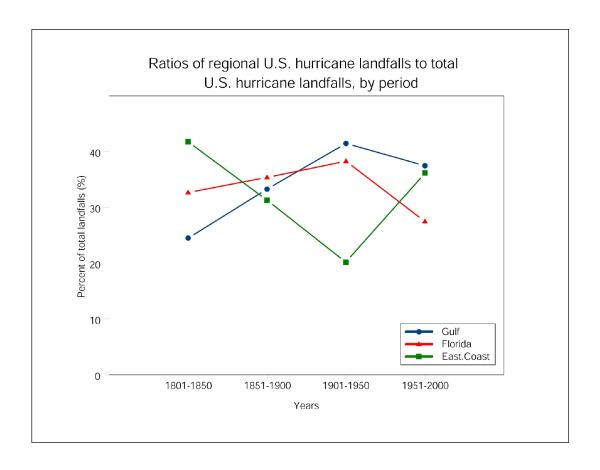


FIGURE 17. Ratios of regional U.S. hurricane landfalls versus total landfalls, by period.

CHAPTER 6

CLIMATE INFLUENCES ON U.S. HURRICANES

6.1 Introduction and Motivation (NAO, ENSO, PDO)

Some of the preceding discussion focused on trends in U.S. total and regional hurricane activity. Here, climate influences on landfall occurrence and location are examined. In particular, the influence of ENSO, the NAO, and the PDO on U.S. hurricane landfalls is addressed.

Many causative mechanisms of tropical cyclone formation are known. Gray (1968; 1984) describes the tropical elements involved in hurricane formation including Caribbean basin sealevel anomalies, the Quasi-Biennial Oscillation (QBO), and the impact of ENSO on hurricane development. El Niño acts to suppress hurricane formation in the North Atlantic, and the counter-climate regime, La Niña, is more favorable for hurricane development (Bove et al. 1998b).

Studies demonstrate that extra-tropical climate features such as the North Atlantic Oscillation (NAO) (Elsner and Kocher 2000) and the tropical Madden-Julian Oscillation (MJO) (Maloney and Hartmann 2000) help to influence hurricane formation and track. Other features may influence the hurricane activity and track in the North Atlantic. Solar activity, volcanic eruptions, and changes in the thermohaline circulation of the North Atlantic are currently under investigation for their impacts on tropical cyclones. Some studies performed on solar activity (Cohen and Sweetser 1974; Liu et al. 2001) indicate that the sunspot cycle may influence tropical cyclones due to fluctuations in solar irradiance, but this theory is still being debated. Additional studies on volcanic eruptions and climate features (Elsner and Kara 1999; Angell and Korshover 1985; Mass and Portman 1989) suggest a possible link between the two geophenomenon.

The North Atlantic basin includes the Caribbean Sea and the Gulf of Mexico. Elsner et al. (2000a) note a change in the hurricane rates in the North Atlantic basin at several change points during the 20th century, with the most recent change in rates of hurricane occurrence taking place in the mid-1990's. Empirical and statistical research (Elsner and Kocher 2000; Elsner et al. 1999; Gray et al. 1992) identify climate factors that contribute to conditions favorable for hurricanes over the North Atlantic basin. These factors influence the occurrence of hurricanes differently depending on the particular region of the basin. For instance, the effect of an El Niño on hurricane frequency over the entire North Atlantic basin is significant, but El Niño's influence on the frequency of hurricanes forming over the subtropics is small. In fact, additional climate factors are usually needed to explain the variation of hurricane activity locally (Jagger et al. 2001; Lehmiller et al. 1997). During some years there is a tendency for hurricanes to track westward through the Caribbean Sea and threaten Mexico and the United States. During other times they tend to move parallel to the east coast of the United States (Elsner et al. 2000b; Elsner et al. 2001). To some extent therefore, the degree to which the Gulf coast is vulnerable to a hurricane in a given year is inversely related to the degree to which the east coast is vulnerable.

Taking into account these climatic factors, several hurricane researchers now produce seasonal forecasts of hurricane activity. Gray (1984) was the pioneer of this forecasting method for the North Atlantic. Forecasting schemes typically deliver a forecast of the number of named storms, number of hurricanes, and number of intense hurricanes in the Atlantic basin. Lehmiller et al. (1997) describe a landfall probability model for the southeastern U.S. coast. Forecasts of hurricane activity along the coast in areas smaller than large regions (i.e., smaller than Gulf Coast or SE Coast) are being experimented with in some climate prediction laboratories.

Cohen and Sweetser (1974) describe an apparent relationship between the solar cycle and Atlantic tropical cyclones. Liu et al. (2001) demonstrates that the most active period for landfalls in the Guangdong province of China over a 1000+ year period of record occurred during the Maunder Minimum, when sunspot numbers were near zero. Elsner and Kavlakov (2001, in review) note a correlation between geomagnetic activity and hurricane intensity for baroclinically-initiated hurricanes in the North Atlantic. They

hypothesize that ionization in the upper atmosphere leads to glaciation at cloud tops, resulting in the release of latent heat and subsequent hurricane intensification. Elsner and Kara (1999) note a slight increase in all North Atlantic hurricanes in the period leading up to and including the 11-year sunspot extremes, and a much stronger relationship between sunspot activity and baroclinic hurricane activity.

Several studies have examined the relationship between volcanic eruptions and climate features (Angell and Korshover 1985; Mass and Portman 1989). Elsner and Kara (1999) examine North Atlantic hurricanes in relation to 10 large volcanic eruptions between 1883 and 1992. They find that major volcanic eruptions result in an increase in hurricane numbers three (26% increase) to four (20% increase) years following such an event.

Further investigations into the tropical factors of hurricane formation and intensity have determined that the global thermohaline circulation of the oceans and the amount of summer rainfall which occurs in the Western Sahel region of West Africa (Gray 1990; Gray and Landsea 1992) correlate with changes in seasonal hurricane number and intensity values. The temperature of the South Atlantic correlates with the amount of precipitation that occurs in the Sahel region of West Africa; this, in turn, affects the number of storms that travel out to sea as westerly waves during hurricane season (Gray and Landsea 1992). These waves have the potential to develop into tropical cyclones if the requisite atmospheric conditions are present during hurricane season.

6.1.1 ENSO (El Niño/La Niña)

ENSO refers to an oscillation of the ocean and atmosphere characterized by seasurface temperature (SST) and sea-level pressure (SLP) changes in the tropical Pacific ocean. El Niño is the warm phase, which results in warming of SST's in the eastern tropical Pacific. The counter-regime, La Niña, results in cool SST's in the same region of the eastern Pacific (Bove et al. 1998a). Another component of the ENSO process is a coupled SLP variation called the Southern Oscillation Index (SOI). The SOI represents the difference in SLP's between Tahiti and Darwin, Australia. The SOI is known to be quite noisy, and is difficult to use as an independent indicator of the phase of ENSO

(Bove et al. 1998a; Elsner and Kara 1999). Therefore, only the ENSO data pertaining to SST's will be utilized in this research.

El Niño has teleconnections to U.S. hurricane landfalls. El Niño acts to suppress hurricane formation in the North Atlantic, and the counter-climate regime, La Niña, is more favorable for hurricane development (Bove et al. 1998b). Caviedes (1991) demonstrated a 500-year dataset detailing significant correlations between hurricane landfalls and El Niño events. Additionally, Elsner et al. (2001) note significant changes in the relationship between El Niño and U.S. hurricane landfalls over the last 150 years. A study of proxy records of ENSO details that the El Niño cycle that we see today (approximately four-year periodicity) is a recent development in the data record, and that ENSO cycles in the late 1800's lasted between 10 and 15 years (Dunbar 2000). Saunders et al. (2000) examines ENSO's influence on both Atlantic hurricanes and NW Pacific typhoons in order to improve predictability of landfalls.

6.1.2 North Atlantic Oscillation (NAO)

The NAO is a coherent seesaw pattern in SLP's between the Azores and Iceland (Elsner and Kocher 2000). Changes in the NAO are thought to affect the tracks of tropical cyclones in the North Atlantic (Elsner et al. 2000b). For example, when the NAO is positive (negative), the Atlantic subtropical high shifts eastward (westward) and gains strength (weakens), steering tropical cyclones along the eastern seaboard (into the Gulf of Mexico). The strength of this association over time will be examined in this research.

The NAO Index (NAOI) is a normalized pressure difference between Iceland and the Azores. When the NAOI values are positive, the subtropical high pressure over the North Atlantic is stronger and located more to the east in the Atlantic. This allows for more recurving storms, potentially indicating a greater risk for storms to make landfall in the northeast U.S. In contrast, a negative NAOI results in a subtropical high pressure situated more to the south and west, and relatively weaker than the positive NAOI counterpart. This situation results in tropical cyclones being steered more to the south, and often results in tropical cyclones threatening landfall along the coastline south of 35 N (Elsner 2001, in review). Analysis of the state of the North Atlantic Oscillation (NAO) indicates that the Gulf coast of the U.S. is more susceptible to major hurricane

landfalls during a relaxed phase of the NAO, whereas the East coast of the U.S. is more susceptible to a major hurricane landfall during an exited phase of the NAO (Elsner et al. 2000b).

6.1.3 PDO (Pacific Decadal Oscillation)

The Pacific Decadal Oscillation (PDO) is an ENSO-like interdecadal variability (Mantua et al. 1997; Zhang et al. 1997) that is the dominant factor in monthly SST variability in the North Pacific (north of about 20 N latitude) (Mantua et al. 1997; Hare and Mantua 2000). The PDO is thought to have its greatest climate manifestations on the climate over the North America and the North Pacific (Zhang et al. 1997). Studies have demonstrated a possible link between modes of the PDO and droughts in the U.S. (Nigam et al. 1999) and teleconnections between the phases of ENSO and the PDO and western U.S. precipitation (Mantua 1999; McCabe and Dettinger 1999).

6.1.4 Data

ENSO data are in the form of Nino 3.0 annual averages (anomalies). The data from 1800 to 1980 are calibrated reconstructions from tree-ring proxies (Mann et al. 2000). The data from 1981 to 1998 are instrumental Nino 3.0 annual averages (anomalies). The data are available online in the Earth Interactions report (under the Spatial Patterns section) available through NOAA's paleoclimatology website (www.ngdc.noaa.gov/paleo/ei/ei_cover.html). Data for 1999 and 2000 are annual averages of Nino 3.0 anomalies based on monthly data available online at (http://www.cpc.ncep.noaa.gov/data/indices/index.html) under the SST subheading (Monthly).

The data for the NAO are well-verified annual reconstructions from tree ring proxies for 1800-1979 (DJFM), and are from Cook et al. (2002), with regression scaled instrumental 1980-2000 data appended. The winter season (year) is assigned to the year in which the January value falls. The data are available online at (http://www.ngdc.noaa.gov/paleo/pubs/cook2002/cook2002.html).

The PDO data from 1800-1991 are well-verified annual reconstructions from treering proxies as described in Biondi et al. (2001). The data are available online at (http://www.ngdc.noaa.gov/paleo/pubs/biondi2001/biondi2001.html). For the 1992-2000 period, annualized PDO values (anomalies) are averaged from monthly data available at N. Mantua's *JISAO* website at the Univ. of Washington. Data are online at (ftp://ftp.atmos.washington.edu/mantua/pnw_impacts/INDICES/PDO.latest).

6.2 Bootstrapping the annual means

The use of terciles in statistical analysis is not new. Tercile data is commonly used in climate studies (e.g., Tennant and Hewitson 2002; Berri et al. 2002; Jury et al. 1999). The tercile approach utilizes three groupings. Here, 50 years of data are present for each of the four periods. We therefore utilize the highest and lowest 15 values in each period in a bootstrap procedure, while the middle tercile (20 values) is excluded from analysis. Data for ENSO, the NAO, and the PDO were gathered for each fifty-year period. Each climate data set was ranked from lowest to highest values. For example, the ENSO data was ranked from lowest values to highest values (e.g., from approximately—1 to 2.62) and the landfall count data associated with the highest 15 values (years) and the lowest 15 values (years) in each 50-year period were then utilized in a bootstrap procedure to estimate the mean annual number of U.S. hurricane landfalls during those years. The procedure was repeated for the other two climate variables (NAO and PDO).

Traditional parametric sampling techniques utilize assumptions about the shape of the population's distribution (assumed to be normally distributed), as well as mean and standard deviation; the bootstrap makes no such assumptions. The bootstrap is a computationally intensive, nonparametric technique for making probability-based inferences about a population characteristic, , based on an estimator, using a sample drawn from that population. The bootstrap procedure empirically estimates the entire sampling distribution of by examining the variation of the statistic within the sample (Mooney and Duval 1993). It differs from the usual parametric inference approach in that it utilizes large numbers of computations to estimate the shape of the sampling distribution for a statistic, instead of the distributional assumptions and formulas typically used for inference. It involves resampling the data with replacement many times (here 1000 times) to create an estimate of the entire sampling distribution of a statistic (each resample mean is called a "replicate")(Mooney and Duval 1993). The result is a

bootstrapped mean value (the mean of resample means) along with standard error (that has not been linked to a parametric distribution). This makes the bootstrap well suited for determining means and standard error for data that may not be normally distributed.

6.3 Bootstrap Results

Figure 18 depicts the mean annual number of U.S. hurricanes for each period, divided into years with the 15 highest and 15 lowest values for each of the three climate variables. The top graph is the mean annual landfall values for ENSO (E1Niño/La Niña). Note that in the last three 50-year periods, the mean annual number of landfalls is higher when the ENSO values are lower. This supports the assertion that La Niña is more favorable for U.S. hurricanes than El Niño (highest values). However, also of note is that the relationship between ENSO and U.S. hurricanes is different in the first 50-year period, 1801-1850. The middle graph (NAO) notes a similar pattern to that for ENSO. The most recent 150 years exhibits a negative relationship between U.S. hurricanes and the strength of the NAO. The first 50-year period, however, demonstrates an opposite relationship. The bottom graph depicts the PDO. In this case, the first, third, and last 50-year periods are similar in noting a negative relationship between U.S. hurricanes and the strength of the PDO, with the second period deviating from the other three.

In order to determine if the size of the hurricane record in the 1801-1850 period affected the indicated relationship with climate features, the data was reexamined using the same bootstrap procedure, but the size of the collated hurricane list was varied. In Figure 19, the first set of columns represents the same data found in Figure 18 for the 1801-1850 period. The collated hurricane list was then modified by adding the 21 tropical storms from the HHIT to the hurricane list, thereby raising the total number of tropical cyclones analyzed via the bootstrap procedure (Hurricanes & all TS). The data was also reanalyzed by utilizing the original collated hurricane list from 1801-1850, but with the 8 most likely candidates for hurricane status instead of tropical storm status added (Hurricanes & some TS). As Figure 19 depicts, the relationship noted in Figure 18 is robust to sample size. The relationship between hurricanes and ENSO, the NAO, and the PDO in the first epoch (1801-1850) is different than in the last three epochs (1851-2000).

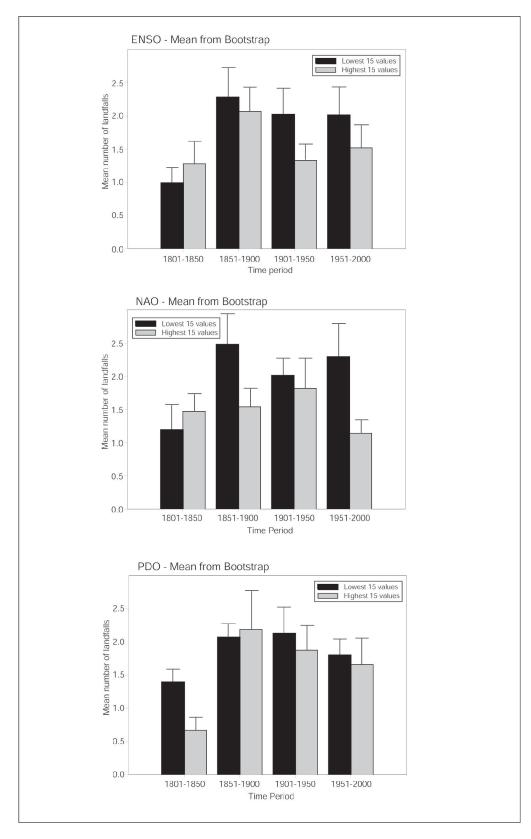


FIGURE 18. U.S. mean annual landfalls based on bootstrap estimates.

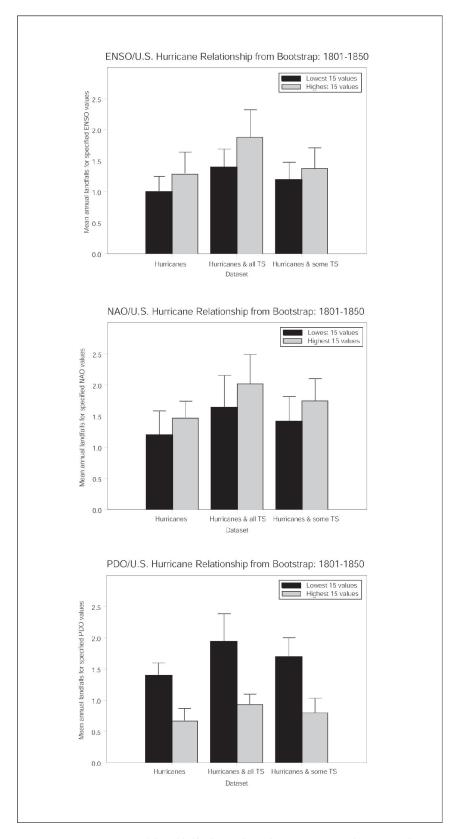


FIGURE 19. U.S. mean annual landfalls based on bootstrap estimates when the sample size is varied.

Additionally, the effect of changing the number of values considered in the bootstrap procedure on the robustness of the climate/hurricane relationship was examined (Figures 20 through 23). In Figure 20, the number of years of selected values is different for each of the three vertical bar sets. The first set represents the originally selected 15 years of values. The second set represents 20 years of selected values and the third set represents 10 years of selected values. There are slight changes to the ENSO and NAO relationships during the 1801-1850 period. As the number of selected values increases for the ENSO data, the relationship between ENSO and U.S. hurricanes becomes less clear. As the number of selected NAO values increases, the relationship between the NAO and U.S. hurricanes is strengthened. This relationship is opposite of that apparent in Figure 18 for the other three epochs. For the PDO, Figure 20 demonstrates no significant difference in relationship based on the number of years of selected PDO values. Figure 23, which depicts a similar layout to Figure 20, but for the 1951-2000 period, underscores the difference in relationship across epochs for U.S. hurricanes and ENSO and the NAO. The PDO demonstrates no obvious trend in relationship depending on the number of years of selected values. There appears to be less of a PDO influence on U.S. hurricanes in the later data.

Due to the uncertainty inherent in the early U.S. hurricane dataset, an additional method of statistical analysis to incorporate uncertainty was utilized. Instead of using absolute landfall counts, as in the previous paragraphs, we used annual rankings of landfall in the bootstrap procedure. In other words, for the 50 years of the collated hurricane list from 1801-1850, each year was ranked based on the total landfall count. Therefore the year with the most landfalls would receive a ranking of 50, and the year with the least landfalls would receive a 1. In reality, due to the fact that the number of landfalls in any one year is relatively small, many rankings were tie values. These rankings were obtained for the collated hurricane list, the list with all tropical storms from the HHIT added, and the list with some of the tropical storms from the HHIT added. The results of the bootstrap procedure are depicted in Figure 24. As can be seen in the figure, the results are similar to those received through the bootstrapping of the absolute counts. This lends evidence to the conclusion that there appears to have been a shift in climate influences on U.S. hurricanes since the mid-19th century.

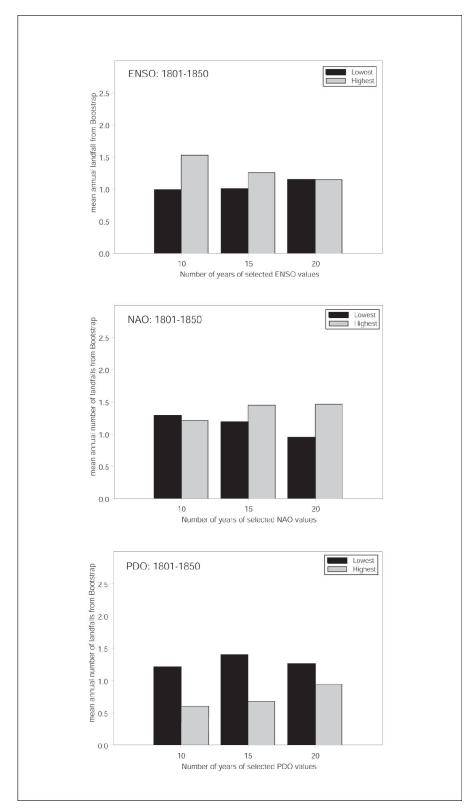


FIGURE 20. U.S. mean annual landfalls based on bootstrap estimates when the number of selected values is varied, 1801-1850.

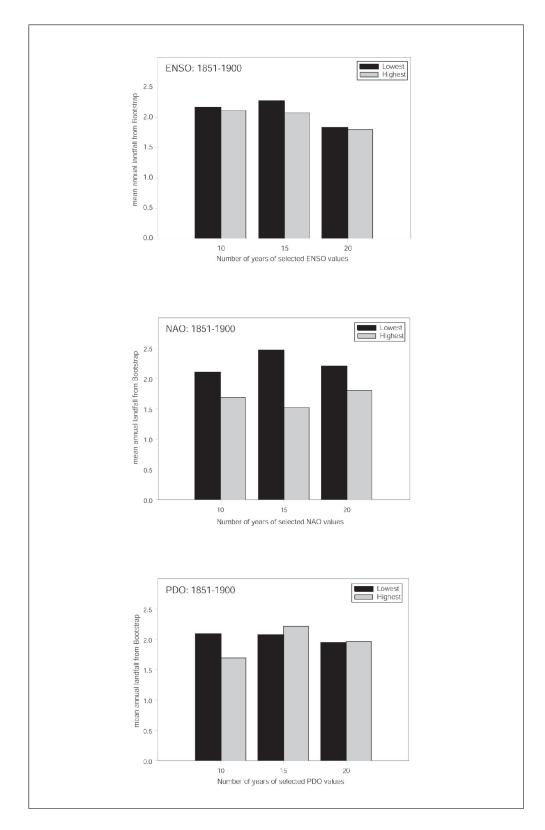


FIGURE 21. U.S. mean annual landfalls based on bootstrap estimates when the number of selected values is varied, 1851-1900.

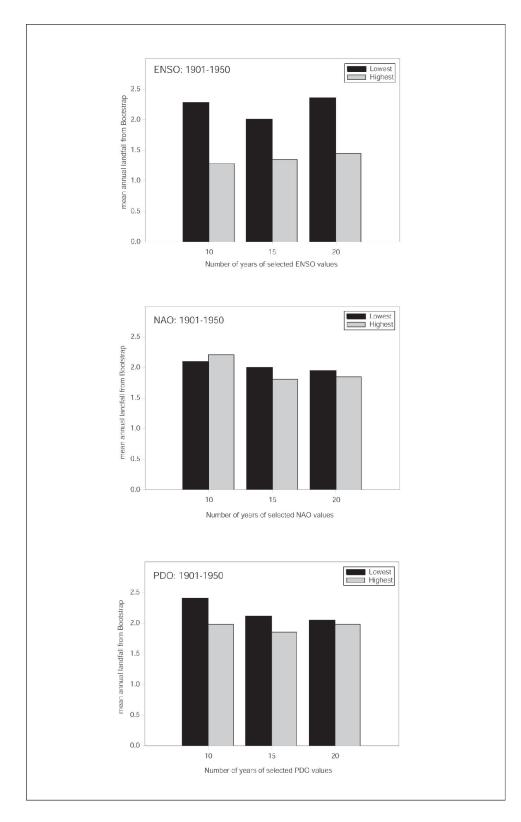


FIGURE 22. U.S. mean annual landfalls based on bootstrap estimates when the number of selected values is varied, 1901-1950.

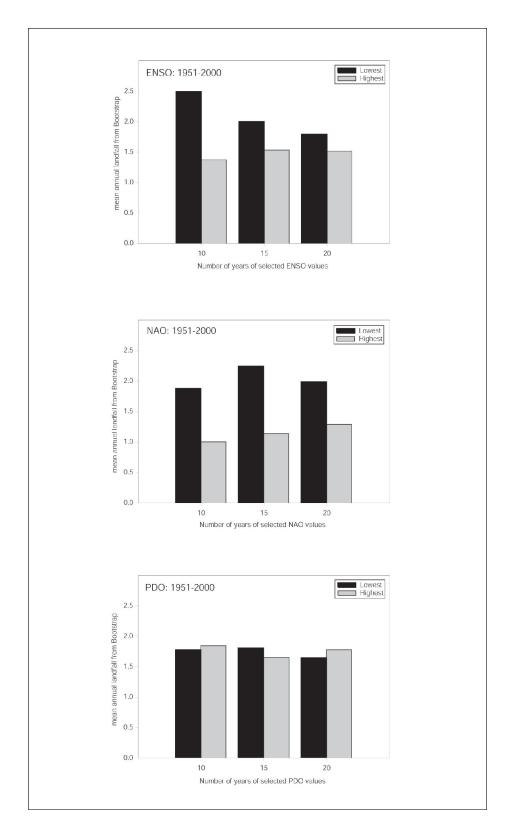


FIGURE 23. U.S. mean annual landfalls based on bootstrap estimates when the number of selected values is varied, 1951-2000.

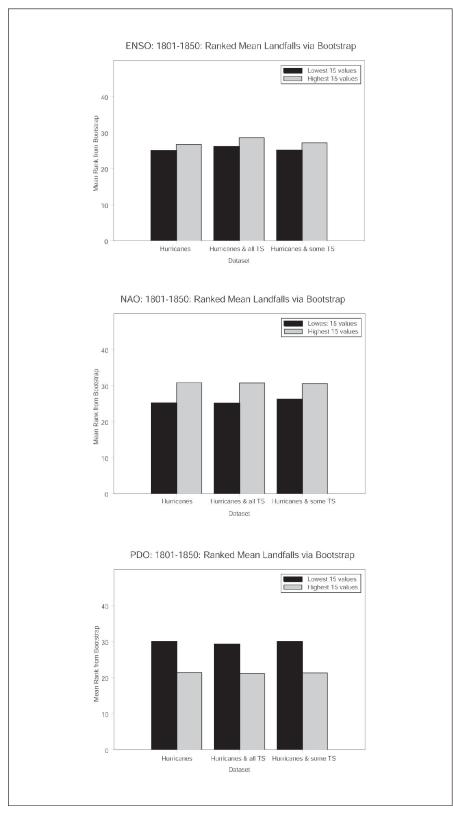


FIGURE 24. U.S. ranked mean landfalls based on bootstrap estimates when the sample size is varied.

6.3.1 Conditioning Plots of Climate Variables

I decided to explore these results further to determine if significant differences existed between the annual means for the 1800-1850 period and the 1851-2000 period for each of the three climate variables utilized (ENSO, NAO, PDO). For each of the three climate variables, two conditioning plots were produced. One conditioning plot depicted the climate variable in the 1800-1850 period while the second conditioning plot depicted the 1851-2000 period. For each of the plots, the x-axis is the value of the indicated climate variable while the y-axis is the landfall count. A slope value and standard error were produced by using a linear regression model to calculate a coefficient and S.E. for each of the plots conditioned on the time period (epoch). The slope values and standard errors are included in each of the conditioning plots. Figure 25 exhibits the conditioning plots.

The ENSO conditioning plots depict a slight divergence in the slopes, with a slight positive trend in the first 50-year period and a slight negative trend in the later 150-year period. The divergence does not appear to be significant. Based on the results of the regression model containing the indicator variable and interaction terms described in the previous section, there is no evidence to suggest a significant difference in mean landfall counts between the two epochs. The NAO conditioning plots depict very similar negative slopes. Both visually and based on the results of the interaction-included regression model, there does not appear to be a significant difference in the mean landfall counts of the two periods. The PDO plots exhibit a slight negative slope in the earlier period, and a completely flat slope in the last 150 years.

An examination of the conditioning plots does not lend support to the conclusions drawn from the bootstrap analysis. One likely explanation includes the fact that I utilized extreme values for the bootstrap analysis instead of using all of the values available as was done in the conditioning plots. In addition, there are relatively few data values in the first 50-year epoch when compared with the second epoch. The more data values present, the more likely a significant trend can be determined.

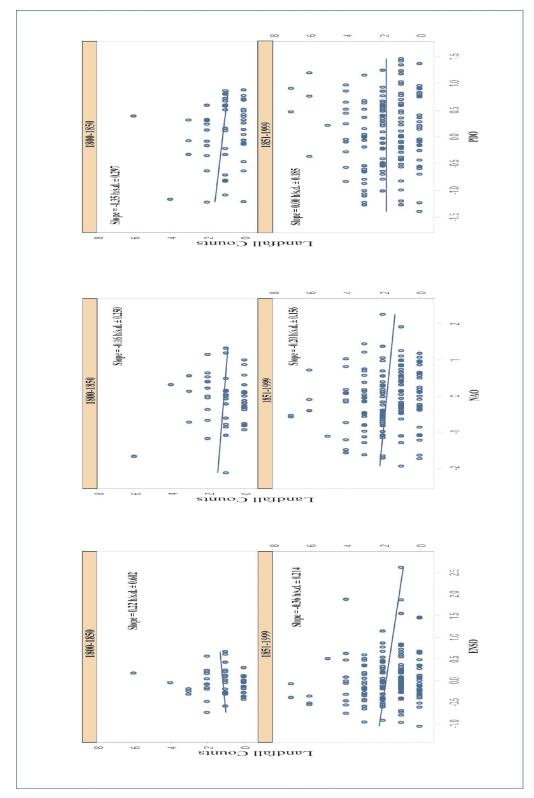


FIGURE 25. Conditioning plots (Trellis graphs) showing the changes in mean annual hurricane landfalls based on climate variables and conditioned on early versus late period.

6.4 Regression analysis

Generalized linear models (McCullagh and Nelder 1989; Gill 2001) - GLM's – can be utilized to describe the interannual relationship of hurricanes to climate features. GLM's are utilized in this research instead of traditional linear regression models because traditional linear regression models assume the response variable is continuous; annual hurricane counts are discrete responses and therefore require a different statistical approach. A GLM is a probability model in which the mean of the response variable (μ) is related to explanatory variables (*p* covariates) through a regression equation (Ramsey and Shafer, 1997).

The equation takes the form:

$$g(\mu) = \beta_0 + \beta_1 X_1 + \dots + \beta_p X_p$$
 (2)

and the GLM uses a specified function of μ which is called the link function, $g(\mu)$, that depends on the type of response variable. All GLM calculations were carried out on the SPLUS software package.

In this statistical analysis, the response variable μ is the hurricane count and the covariates p are the climate factors such as ENSO and the NAO. Poisson regression is a special case of the generalized linear model and is utilized here. Poisson regression is suited for describing the annual count of hurricanes, which are discrete counts.

6.4.1 Poisson Regression

Hurricane landfalls totals are counts of landfall occurrences that occur over a period of time (and space), and have no defined upper bound. The Poisson probability distribution can be used to describe the population distribution for this kind of count data. It is most useful for counts of rare events that occur at random points in time or space, and it can be utilized in a larger group of issues in which count data demonstrate an increasing spread with an increasing mean. The Poisson distribution is a form of the binomial distribution for large number of trials with small probabilities of an occurrence on any given trial (see e.g., Elsner and Schmertmann 1993). The limiting form of the distribution sets no theoretical limit so it works well for modeling the annual count of hurricanes or typho ons. As an example, the probability of Y U. S. hurricanes is:

$$\Pr\{Y\} = \exp(-\lambda)\lambda^{Y}/Y!, \text{ for } Y = 0, 1, 2, ...$$
 (3)

where λ is the annual average and variance (the variance is equal to the mean). The Poisson distribution is skewed to the right with the skewness most pronounced for small λ . For large λ , the distribution is approximated by the normal distribution.

With a count response (annual number of U. S. hurricanes) and covariates, the Poisson generalized linear model specifies that the distribution of tropical cyclones is Poisson (see Elsner et al. 2001) and that the natural logarithm of the mean (link function) is linear in the regression coefficients. A sample Poisson generalized linear model utilized to determine all hurricanes to strike the U.S. coast (USH) could be:

$$log(USH) = 0.4597 + 0.0684 \times ENSO - 0.0793 \times NAOI + 0.1031 \times PDO + error$$
 (4)

where a maximum likelihood procedure is again used to estimate the coefficients. A quantile plot can be used to indicate the presence of a reasonable model. An analysis of variance (ANOVA) utilizing a chi-square goodness-of-fit test can again be used to determine whether climatic factors are important (statistically significant).

Poisson log-linear regression does not involve a transformation of the response variable. The link function, which relates the response variable to the explanatory variables is the logarithm. Therefore, if the Poisson log-linear model is used to determine the number of U.S. hurricane landfalls based on the value of ENSO, the number of hurricane landfalls would be expected to be Poisson distributed, and the mean number of landfalls based on the value of ENSO could be specified by a model such as:

$$log(\mu) = \beta_0 + \beta_1 ENSO$$
 (5) or as an alternative, $\mu = exp(\beta_0 + \beta_1 ENSO)$ (6)

This indicates that a one unit increase in ENSO is associated with a *Y*-fold increase in the mean number of hurricane landfalls, where $Y = \exp(\beta_I)$ (Ramsey and Schafer 1997). As an example, assume that the estimate (coefficient) of β_I is 0.100. In this hypothetical case, a 1-unit increase in the value of ENSO would result in an approximate 1.1-fold change in the mean number of hurricane landfalls, or a 10% increase in the mean number of hurricane landfalls for every additional 1-unit increase in ENSO.

Table 8 lists the results of Poisson regression performed on U.S. hurricanes along the entire coastline. Over the entire period of record, Year and ENSO are significant at the 95% threshold, while the NAO is significant at the 90% threshold. The fact that Year is significant indicates a definite linear trend in the data; more hurricanes are reported later in the entire period of record than earlier. ENSO is most significant during the 1901-1950 period, while Year is most significant during the 1851-1900 period. Neither the NAO nor the PDO were significant during any 50-year period.

Tables 9 (Gulf coast) and 10 (Florida) examine the effects of the same climate variables on the two most active regions of the coastline. For the Gulf coast, YEAR, NAO, and PDO are significant at the 90% threshold or higher over the entire period of record. ENSO is not statistically significant. The PDO is a significant climate variable during the 1851-1900 period. In fact, the PDO is the most significant climate variable in the Gulf coast region over the last 200 years. For Florida, none of the climate variables were significant over the entire period of record. YEAR was significant for the first three 50-year periods, and ENSO was significant in the 1901-1950 period.

I was particularly interested to determine if the regression models would demonstrate any significant difference between the mean annual landfall counts in the first 50-year period compared with the last 150-years. Although the bootstrap analysis suggested some potential changes in the influence of dominant climate modes on U.S. hurricane landfalls, these analysis utilized extreme values (top 10, 15, or 20 values for the climate variables). The regression model I utilized to examine these interesting bootstrap results contained an indicator variable based on the epoch and interaction terms between the epoch and the climate variables. An indicator variable (also called a "dummy variable") is used to indicate that an attribute is present. Typically, an indicator variable has a value of 1 (if an attribute is present) or 0 (if an attribute is not present). In this case, the epoch was added to the dataset as an indicator variable, and the 1800-1850 period was coded as a "0" while the 1851-2000 period was coded a "1". Thus, the indicator variable served to create a distinction between the first epoch (which was of greatest interest) and the second larger epoch.

Along with the inclusion of an indicator variable, the model incorporated interaction terms for the climate variables based on the epoch. Two variables are

TABLE 8: Poisson regression results for all U.S. hurricanes, segregated by variable.

Year:

Time Period	Coefficient	S.E.	t-val	p-val	
1801-1850	0.012	0.009	1.221	0.104	
1851-1900	0.015	0.007	2.144	0.028	
1901-1950	0.010	0.007	1.298	0.165	
1951-2000	-0.001	0.010	-0.136	0.852	
1801-2000	0.002	0.000	2.689	0.019	

ENSO:

Time Period	Coefficient	S.E.	t-val	p-val
1801-1850	0.096	0.511	0.189	0.798
1851-1900	0.139	0.274	0.509	0.622
1901-1950	-0.507	0.233	-2.169	0.027
1951-2000	-0.213	0.190	-1.117	0.400
1801-2000	-0.235	0.114	-2.046	0.041

NAO:

Time Period	Coefficient	S.E.	t-val	p-val	
1801-1850	-0.116	0.207	-0.561	0.703	
1851-1900	-0.045	0.143	-0.315	0.738	
1901-1950	-0.048	0.142	-0.338	0.748	
1951-2000	-0.202	0.135	-1.488	0.117	
1801-2000	-0.125	0.072	-1.728	0.084	

PDO:

Time Period	Coefficient	S.E.	t-val	p-val	
1801-1850	-0.256	0.234	-1.095	0.277	
1851-1900	0.043	0.174	0.247	0.805	
1901-1950	-0.024	0.178	-0.135	0.892	
1951-2000	0.168	0.213	0.791	0.427	
1801-2000	-0.008	0.085	-0.093	0.925	

TABLE 9: Poisson regression results for Gulf coast hurricanes, segregated by variable.

YEAR:

Time Period	Coefficient	S.E.	t-val	p-val	
1801-1850	0.042	0.021	1.922	0.027	
1851-1900	0.002	0.012	0.233	0.960	
1901-1950	0.012	0.012	1.005	0.453	
1951-2000	-0.001	0.016	-0.082	0.676	
1801-2000	0.004	0.001	2.807	0.012	

ENSO:

Time Period	Coefficient	S.E.	t-val	p-val	
1801-1850	-0.443	0.998	-0.444	0.892	
1851-1900	0.066	0.492	0.135	0.958	
1901-1950	-0.438	0.359	-1.219	0.204	
1951-2000	-0.141	0.294	0.481	0.911	
1801-2000	-0.284	0.179	-1.583	0.220	

NAO:

Time Period	Coefficient	S.E.	t-val	p-val	
1801-1850	-0.429	0.384	-1.115	0.265	
1851-1900	-0.421	0.272	-1.543	0.112	
1901-1950	-0.140	0.221	-0.634	0.424	
1951-2000	-0.034	0.223	-0.156	0.817	
1801-2000	-0.218	0.122	-1.778	0.074	

PDO:

Time Period	Coefficient	S.E.	t-val	p-val	
1801-1850	0.008	0.497	0.017	0.985	
1851-1900	0.524	0.315	1.662	0.096	
1901-1950	0.294	0.299	0.983	0.313	
1951-2000	0.282	0.345	0.819	0.411	
1801-2000	0.319	0.145	2.195	0.027	
	1801-1850 1851-1900 1901-1950 1951-2000	1801-1850 0.008 1851-1900 0.524 1901-1950 0.294 1951-2000 0.282	1801-1850 0.008 0.497 1851-1900 0.524 0.315 1901-1950 0.294 0.299 1951-2000 0.282 0.345	1801-1850 0.008 0.497 0.017 1851-1900 0.524 0.315 1.662 1901-1950 0.294 0.299 0.983 1951-2000 0.282 0.345 0.819	1801-1850 0.008 0.497 0.017 0.985 1851-1900 0.524 0.315 1.662 0.096 1901-1950 0.294 0.299 0.983 0.313 1951-2000 0.282 0.345 0.819 0.411

TABLE 10: Poisson regression results for Florida, segregated by variable.

YEAR:

Time Period	Coefficient	S.E.	t-val	p-val	
1801-1850	0.028	0.018	1.506	0.040	
1851-1900	0.021	0.012	1.658	0.065	
1901-1950	0.017	0.012	1.379	0.083	
1951-2000	0.013	0.018	0.725	0.711	
1801-2000	0.002	0.001	1.487	0.158	

ENSO:

Time Period	Coefficient	S.E.	t-val	p-val
1801-1850	0.228	0.912	0.249	0.554
1851-1900	0.448	0.456	0.981	0.300
1901-1950	-0.728	0.404	-1.800	0.051
1951-2000	0.158	0.335	0.473	0.808
1801-2000	-0.158	0.199	-0.797	0.325

NAO:

Time Period	Coefficient	S.E.	t-val	p-val	
1801-1850	-0.531	0.351	-1.513	0.226	
1851-1900	0.137	0.230	0.598	0.528	
1901-1950	0.059	0.233	0.255	0.721	
1951-2000	-0.201	0.262	-0.770	0.464	
1801-2000	-0.051	0.123	-0.415	0.689	

PDO:

Time Period	Coefficient	S.E.	t-val	p-val	
1801-1850	-0.528	0.420	-1.256	0.210	
1851-1900	-0.106	0.295	-0.361	0.717	
1901-1950	-0.174	0.282	-0.617	0.541	
1951-2000	-0.229	0.399	-0.574	0.567	
1801-2000	-0.178	0.147	-1.210	0.228	

considered to interact if the effect that one of the variables has on the mean of the response variable is dependent on the value of the other (Ramsey and Shafer 1997). The question I was trying to answer with the inclusion of these interaction terms was: Does the effect of one (or all) of these climate variables on U.S. hurricane landfall depend on the epoch in which the activity occurs? The simplified model utilized was:

$$Landfalls = ENSO + NAO + PDO + Epoch:ENSO + Epoch:NAO + Epoch:PDO (7)$$

where a colon is utilized to signify interaction terms and Epoch is the indicator variable.

The results of this Poisson regression model with interaction terms suggests that there is no significant difference present in the interaction terms. Therefore, the effect of one (or in this case, all) of the climate variables on U.S. hurricane landfalls was not significantly different between the epochs. The lowest interaction term p-value was 0.128 for the PDO interaction term. The results are listed in Table 11.

TABLE 11: Poisson regression results from a model with an indicator variable and interaction terms.

Variable	Coefficient	S.E.	t-val	p-val
ENSO	0.364	0.411	0.885	0.126
NAO	-0.037	0.169	-0.223	0.092
PDO	-0.282	0.186	-1.511	0.766
Epoch:ENSO	-0.596	0.429	-1.388	0.238
Epoch:NAO	-0.102	0.186	-0.548	0.473
Epoch:PDO	0.322	0.210	1.533	0.128

6.5 Sunspots

The annual means of Wolf (Zurich) sunspot numbers are commonly used in studies involving climate-solar interactions (Elsner et al. 1999) and will be utilized in this research to examine the effects of sunspots on hurricane activity. Elsner and Kara (1999) noted only slight increases in North Atlantic basin hurricanes during solar activity extremes. The increase was more apparent, however, among baroclinic hurricane activity. No significant relationship between solar activity and U.S. hurricanes was described. This work expands on Elsner and Kara (1999) to include the years from 1800 to 1850 in the solar activity investigation. Sunspot data will be obtained through the website of the Sunspot Index Data Center at the Royal Observatory of Belgium (http://sidc.oma.be/index.php3). The data exist from 1749 in monthly sunspot numbers and from 1700 in yearly sunspot numbers, and the data are based on direct astronomical observations. A smoothed sunspot number is also available as an option.

Results of the Poisson regressions performed utilizing sunspots as a climate variable indicated that sunspots are not a significant climate mode affecting U.S. hurricanes. The lowest p-value of the sunspot data was 0.307, when all of the tropical storms from the HHIT were added to the collated hurricane list for 1801-1850. For the 1851-2000 period, the sunspot p-value was 0.483.

6.6 Volcanic eruptions and U.S. hurricanes

As previously discussed, Elsner and Kara (1999) examined the effect of major volcanic eruptions on hurricane activity in the North Atlantic basin, and they noted a slight increase in hurricane activity both the third (26%) and fourth (20%) years posteruption. My work expands on Elsner and Kara (1999) and notes any similar occurrences in the early 19th century hurricane data. The volcanic eruption data set will consist only of those eruptions known to have sent a large ash cloud into the stratosphere. The data set will comprise those major eruptions known to have occurred between 1800 and 1850; these eruptions include Cosiguina in Nicaragua (1835), Tambora in Indonesia (1815), and La Soufriere in St. Vincent (1812) (Bullard 1962; Blong 1984). Examinations of the effects of volcanic eruptions on tropical cyclone tracks will take place from 5 years before (-5) the year of occurrence (0) to 5 years post-eruption (+5).

Data on the active volcanoes in the Caribbean and Latin America was obtained online at (http://www.oas.org/usde/publications/unit/oea54e/ch19.htm). Additional data and cross-referencing was performed at the website of the Global Volcanism Program, part of the Smithsonian Institute's National Museum of Natural History. The data are available online at (http://www.volcano.si.edu). Table 12 depicts the major volcanic eruptions in Latin America and the Caribbean between 1800 and 2000.

Here an examination U.S. hurricane landfalls following the eruptions of La Soufriere (May 1, 1812) on St. Vincent, Mt. Tambora (April 13, 1815) in Indonesia, and Cosiguina (Jan 22, 1835) in Nicaragua follows. The analysis utilizes the superposed epoch method (e.g., Elsner and Kara 1999) whereby volcanic eruptions are considered separate events, even if years overlap, and the number of U.S. hurricanes occurring before and after the volcanic event is considered. Table 13 depicts the average number of U.S. hurricanes 5 years before the eruption and 5 years after. The results show that while the eruption of Mt. Tambora resulted in slightly fewer U.S. hurricanes in the 5 years following, La Soufriere and Cosiguina are both associated with increased numbers of U.S. hurricanes in the 5 years post-eruption, a finding which supports the work of Elsner and Kara (1999). Table 14 notes the number of hurricane landfalls before and after the events listed in Table 12 for the period 1800-2000. In contrast to the results presented in Table 13, no significant trend in U.S. landfalls is evident in the table. While no significant link is discovered here, volcanic activity may account for some of the global temperature depression noted between 1800 and 1850, which may help explain the dominance of the PDO on U.S. hurricanes in the early 19th century.

6.7 Correlations Among the Covariates

The Pearson Product Moment correlation (commonly known as the sample correlation coefficient or more simply, the correlation) is used to describe the linear association between any two variables (Ramsey and Shafer, 1997). The formula for the Pearson Product Moment correlation is the following:

$$r = \frac{\sum_{i=1}^{n} (x_i - \overline{x})(y_i - \overline{y})}{(n-1)S_x S_y}$$
(5)

TABLE 12: Volcanic eruptions in Latin America and the Caribbean: 1800-2000*

Location	Name	Date(s) of Eruption
Mexico	Colima	1818, 1890, 1913
Mexico	El Chichon	1982
Guatemala	Santa Maria	1902
Guatemala	Fuego	1857, 1880, 1932, 1974
Nicaragua	Cosiguina	1835
Colo mbia	Doña Juana	1897
Ecuador	Cotopaxi	1877
Ecuador	Tunguraha	1886, 1916
Chile (central)	Cerro Azul	1932
Martinique	Pelee	1902
St. Vincent	Soufriere	1812, 1902

^{*}Volcano es with a Volcanic Explosivity Index (VEI) of 4 or higher are included in the table. The VEI is a single numerical description of the size or magnitude of a volcanic eruption; it includes variables such as eruptive cloud heights, duration, tropospheric injection and stratospheric injection. A VEI of 4 is considered a large eruption while a VEI of 8 is cataclysmic. For comparison, the eruption of Mt. Tambora in 1815 has a VEI of 7.

TABLE 13: Average number of U.S. hurricanes 5 years before and 5 years after major volcanic eruptions between 1800-1850. Only the Mt. Tambora eruption resulted in fewer U.S. hurricanes in the 5 years post-eruption. The columns containing the averages with

the "TS included" are explained in the Discussion section of the paper.

Volcanic Eruption (Year)	Average 5 years prior	Average 5 years post	Average 5 years prior (TS included)	Average 5 years post (TS included)
Mt. Tambora (1815)	1.4	0.8	1.6	1.2
La Soufriere (1812)	0.4	1.2	0.8	1.6
Cosiguina (1835)	0.6	1.4	1.0	2.4

TABLE 14: Volcanic Activity and U.S. Hurricane totals: 1800-2000*

Period	-3	-2	-1	0	+1	+2	+3	
1801-1850	4	6	5	5	6	2	6	
1851-1900	13	10	13	17	13	15	15	
1901-1950	17	5	11	12	19	11	11	
1951-2000	7	3	0	1	2	2	8	

^{*}Values are the number of U.S. hurricanes to make landfall during the specified period for

each of the indicated years before, during, and after a major volcanic event.

where S_x and S_y are the sample standard deviations. Due to the fact that the correlation coefficient is symmetric in both the X and Y directions, there is not a response or explanatory variable as in regression.

The correlation coefficient results in a (r) correlation value which falls between -1 and +1. An extreme negative value indicates that the points on the scatterplot will all fall exactly along a line sloping downward (negative), while an extreme positive value will indicate the same on a line sloping positive. A correlation of zero indicates complete uncorrelation, or no linear association between points on a scatterplot. For inferences to be drawn from correlation coefficients, pairs should be selected at random from the population. Causal connections must be intrepreted very carefully; the existence of a linear association does not necessarily imply a cause and effect relationship (Rogerson 2001).

There are many research activities that may require the use of the Pearson Product Moment correlation. For example, Elsner (2003, in press) demonstrated that correlations between landfalls along the southeast coast line and SM storms were strong enough to be useful in analyzing the storm tracks in years prior to complete/accurate track information. Such correlation calculations will be necessary for SM landfalls in China as well as the U.S., and other scenarios, such as correlations between recurving hurricanes and landfalls north of the SC/NC border (or Guangdong province in China), will likely require such correlation determinations.

The correlation coefficient is influenced by the sample size. Correlation values are not subject to absolute cut-off points to determine significance. Table 15 indicates the the minimum values of r required for significance (at $\alpha = 0.05$).

Table 16 depicts the results of the correlations of two of the three most prominent climate modes to affect U.S. hurricane landfalls. Due to the fact that ENSO and the NAO are well-studied, comparing these climate features with the PDO was of primary interest. The results showed that there were no significant correlations in the earlier periods, although there was statistically significant correlation between ENSO and the PDO in the 1951-2000 period.

TABLE 15: The minimum values of r required for significance (at $\alpha = 0.05$) based on sample size (n) (adapted from Rogerson 2001).

Sample Size, n	Minimum value of r for significance ($\alpha = 0.05$)
15	0.514
20	0.444
30	0.361
50	0.279
100	0.197
250	0.124

TABLE 16: Correlations between climate variables, 1801-2000.

Years	Climate Variables	Value	
1801-1850	ENSO-PDO	0.091	
1801-1850	NAO-PDO	-0.109	
1851-1900	ENSO-PDO	-0.167	
1851-1900	NAO-PDO	-0.056	
1901-1950	ENSO-PDO	-0.105	
1901-1950	NAO-PDO	-0.092	
1951-2000	ENSO-PDO	0.515	
1951-2000	NAO-PDO	0.088	

CHAPTER 7

SUMMARY AND CONCLUSION

Most U.S. hurricane climate research is based on records from the past 100 years or so. The official U.S. hurricane record currently extends back to 1851. To better understand these rare but potentially catastrophic events it is important to have the longest possible records. Combining various historical sources, tropical cyclone impacts in the United States have been collated back to the year 1800 (a 25% increase in the number of years from the official record) using a GIS. The Historical Hurricane Information Tool (HHIT) is based on ESRI's ArcView GIS 3.1.

Storm impacts in the United States and to vessels in adjacent coastal waters are manually input on a geographic map using callouts. Descriptive information such as damage reports, meteorological observations, and ship reports are included. Individual historical sources are treated as separate themes for each storm. Storms are listed chronologically by year. Additional value is added to the maps with the inclusion of a possible storm track. Estimated storm intensities at landfall are also included.

Many of the current sources of historical hurricanes are text based. The present work takes these documents and makes them accessible to hurricane researchers, emergency management officials, and climatologists. The cartographic nature of the items provides an enhanced perception of the swath of damage left behind by the storms. Estimated tracks and intensities may be utilized in statistical analysis incorporating these records. The digital nature of these projects makes them suited for editing and modification. The hurricane GIS tool will be made available on CD-ROM. Updates and expansions are anticipated. My work is a reproduction of the quantitative and qualitative information given in the available documents, and it provides an easily accessible source

of information about early American hurricanes that is geographical in nature and digital for ease of use.

The HHIT allows easy access to the hurricane information prior to 1851. The seasonal variability in U.S. hurricanes has been examined from an exploratory perspective. During each four 50-year intervals, including the period 1800-49, the greatest threat of a U.S. hurricane occurs between 8 September and 17 September. The seasonal distributions of landfalls all indicate a slower buildup to the peak with a more abrupt ending. The fewer number of landfalls over the first half of the 19th century is likely due to the fact that some storms went undetected.

More detailed applications have examined the uncertainty inherent in the earlier records in more detail, and it is not necessary to ignore these earlier records completely. In fact, studies (Elsner and Bossak 2001; Elsner and Jagger 2002) demonstrate the use of Bayesian statistics to combine earlier records of lesser accuracy with later records of greater accuracy in hurricane climate forecasts. By incorporating earlier records of U.S. hurricanes with later records, a better understanding of hurricane occurrences over time is developed. This understanding can be utilized, for example, in reinsurance contracts (Michaels et al. 1997) or weather derivatives in the futures market.

The HHIT GIS tool is available through the Hurricane Climate Institute at Florida State University (http://garnet.acns.fsu.edu/~jelsner/www/). The HHIT contains 90 tropical cyclone impacts: 56 U.S. hurricanes, 21 U.S. tropical storms, and 13 offshore hurricanes. A collated list consisting of early U.S. hurricanes has been established for use in statistical analysis. This dataset, combined with hurricane data from NOAA's Hurricane Reanalysis project, provides an unprecedented look at U.S. hurricane activity over the past 200 years (1801-2000).

Analysis of two hundred years of U.S. hurricane data reveals that the most active month for U.S. hurricanes is September, followed by August and October. June and July are the least active months. More activity is present in the 20th century than the 19th century, but this conclusion is subject to revision if new storm records are uncovered pertaining to the 1800-1850 period. The number of hurricanes to strike Florida in recent times is unusually low compared to long-term records. The ratio of major hurricanes to all landfalling hurricanes in the U.S. is highest during the 1801-1850 period.

The variables affecting U.S. hurricanes are possibly in a state of flux. Annual means for hurricane landfalls computed via a bootstrap procedure exhibit a change in the relationship between ENSO/NAO and U.S. hurricanes in the early 19th century data compared to later data. Reanalysis performed with increased sample sizes indicated a robust climate/U.S. hurricane relationship. When the data were analyzed with a change in the number of selected values utilized in the bootstrap, the relationships were still evident, although less significant. The influence of the PDO on U.S. hurricanes appears to have lessened over the last 200 years. However, the bootstrap procedure utilizes only the top and bottom terciles of data for each of the four 50-year periods. Therefore, the results indicated in the bootstrap may not be validated when conducting statistical analysis with all of the data.

The results from the Poisson regressions suggest a possible shift in the climate influences affecting U.S. hurricanes over the last 200 years. ENSO and the NAO are found not to be statistically significant in explaining U.S. hurricanes from 1801-1850, and the PDO and NAO exhibit their greatest influence on Gulf coast hurricanes. Conversely, the PDO is not significant in the later period data, while ENSO and the NAO are the dominant U.S. hurricane climate influences out of the three climate variables examined. The results of this work add one more piece of information to the climate puzzle and are worthy of additional investigation. An additional Poisson regression model which incorporates an indicator variable and interaction terms was utilized to investigate the mean number of U.S. landfalls in the first epoch (1800-1850) in comparison to the second epoch (1851-2000). The results demonstrated no evidence to suggest a significant difference in the mean landfall numbers between the first epoch and the second epoch for each of the three climate variables included. Conditioning plots were created, and these plots demonstrate no obvious significant difference in the U.S. hurricane landfall means. However, the lack of substantial data points in the regression model may have affected the results. Generally, the more data points present, the more likely a statistically significant result will be found.

Elsner et al. (2001) has noted changes in the relationship between ENSO and U.S. hurricanes (as well as teleconnections to the NAO) throughout the 20th century. One study utilizing tree-ring proxies for the PDO (D'Arrigo et al. 2001) noted evidence of

less pronounced interdecadal variability after the mid-nineteenth century. Another study has examined North Pacific modes and U.S. droughts along the east coast (Barlow et al. 2001). The authors suggest that circulation changes due to SST anomalies in the North Pacific cause a disruption the inflow of maritime air from the Gulf of Mexico (possibly offering a physical explanation for the significance of the PDO along the Gulf coast in the 1851-1900 period in explaining hurricane landfalls there), causing a drought along the eastern coastline.

It is hypothesized that the cause of the PDO possibly being the dominant mode of climate influence on U.S. hurricanes between 1801-1850 is cooler global temperatures during this period. The large number of volcanic eruptions which occurred in the first half of the 19th century (after about 1802) likely resulted in a stratospheric dust cloud that cooled the planet slightly, and led to the PDO's dominance. In the last 150 years, as the climate has warmed, the influence of the PDO on U.S. hurricanes has waned dramatically. However, the actual physical explanation for these noted trends is worthy of continued study.

Future work in this topic may include the addition of additional sources of information about historical U.S. hurricanes (such as the digitization of U.S. Army fort data by Andsager and Nicodemus 2003) and the continuing progress of NOAA's Reanalysis project (Landsea et al. 2003) as well as addressing issues of uncertainty in the early 19th Century U.S. hurricane dataset.

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BIOGRAPHICAL SKETCH

The author has been interested in weather and climate since childhood. As a high school student, he was invited to speak to elementary school students about severe weather and climate features. A burgeoning interest in all aspects of the natural world led circuitously to the pursuit of a Bachelor of Science degree in Geography (Physical) at the University of Georgia (UGA), which was completed in 1996. Soon after completion of his Bachelor's degree, the author began further study in Geography (Physical), and completed a Master of Arts degree at UGA in 1998. During his tenure as a graduate student at UGA, the author taught Weather and Climate courses for two academic years. He also spent nearly two years working intermittently full-time and part-time as a Cartographic Technician for the U.S. Geological Survey in Atlanta, GA. Soon after completing his MA, the author accepted a full-time position as remote sensing specialist with the Foreign Agricultural Service, USDA, in Washington, DC. A strong desire to further his education led to his departure from employment in DC in order to obtain a Ph.D. in Geography. The author hopes to find a position which combines weather and climate research with remote sensing and GIS applications.