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An analysis of tropical storm surge trends for the Atlantic coast of the United States

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AN ANALYSIS OF TROPICAL STORM SURGE TRENDS FOR THE ATLANTIC COAST
OF THE UNITED STATES

A Thesis

by
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ABSTRACT

Tropical cyclone generate storm surge is responsible for damage to lives and livelihoods on a global scale. In spite of this inherent danger, the scientific community currently lacks a global database of peak storm surge events. Thus, SURGEDAT was created to fill this void. Research began on the Gulf of Mexico, and the research presented here creates a database of peak surges for the Atlantic Coast of the United States (ACUS) between the years of 1898-2011. A total of 25 sources were utilized for creation of this database, with many more being consulted but not included in the final product. A database of 72 surge events ≥ 1.22 m was created, with the largest event being a 6.49 m surge in Fairhaven, MA in 1938. Spatial analysis reveals high levels of surge activity in south Florida and North Carolina, with diminished activity from Virginia to Maine. Statistical analysis tested surge frequency and magnitude versus two teleconnections: the Atlantic Multidecadal Oscillation (AMO), and the Southern Oscillation Index (SOI). Statistically significant links were found between AMO phase and surge frequencies; however, no links were found between AMO phase and surge height. No statistically significant links between SOI and magnitude or frequency were detected. Return periods associated with surge events were calculated through three quantile estimation methods – the Pareto distribution and the Huff-Angel and Southern Regional Climate Center (SRCC) linear regression methods. The SRCC method produced the best quantile estimates of surge heights along the ACUS, with a 100-yr event of 6.49 m and a 2-yr event of 1.55 m. A K-means cluster analysis was performed to split the ACUS region into 10 zones, and the SRCC method was employed to produce quantile estimates on a regional level. Zone 7, centered on Charleston, SC, produced the highest 100-yr return period (5.64 m), followed by Zone 1, centered on New Bedford, MA (5.61 m).

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

Tropical cyclones generate a number of associated hazards. Among the most financially devastating and deadly of these hazards is storm surge. Extreme storm surges have been responsible for the loss of many lives, especially when surge strikes an area that is socially and structurally under-prepared (Frank and Husain 1971). Costs of rebuilding after a landfalling hurricane can be astronomical, with the 2004-2005 Atlantic hurricane seasons alone resulting in $150 billion in damages (Bjarnadottir et al. 2011). It is clear that cyclones and their associated storm surges represent a large-scale economic and social threat, and any guidance to prepare coastal residents for landfalling storms is of utmost utility. However, the climatological community is currently lacking a historical summation of storm surge heights and vulnerable areas. To fill this void, this thesis creates and analyzes a database of peak surge heights for cyclones affecting the Atlantic Coast of the United States (ACUS). The database contains information that is pertinent to coastal developers, home and business owners, insurance agencies, emergency management officials, and many other stakeholders.

1.2 Surge Generation

1.2.1 Introduction

Storm surge is an abnormal variation in sea surface height due to external forcings, such as that provided by a tropical cyclone (Rego and Li 2009). Persistent strong winds force water to build up in the direction of the wind, usually on-shore. Additionally, low pressure fields associated with tropical cyclones also contributes to a higher sea level, as a 1hPa decrease in pressure tends to correlate with a 1cm rise in sea level (Singh and Aung 2005). It should be noted

that storm surge is not limited to tropical cyclones; however, this research only includes tropically-based cyclones.

1.2.2 Tropical Cyclone Development and Tracking

To determine areas that are vulnerable to surge, one must first determine areas that are vulnerable to tropical cyclones. Thus, some basic climatological and atmospheric cyclonic characteristics will be examined. Sea surface temperatures (SST) greater than 26° are required, thus limiting development regions to roughly $25^{o}N$-$25^{o}S$ (Gray 1998). Tropical cyclones acquire their trademark rotational circulation due to the Coriolis force. Thus, the absence of the Coriolis effect near the Equator inhibits cyclonic development there, leaving a main development region of 5°-25° N/S. Tropospheric wind characteristics also play a role in development, with lower wind shear values encouraging development; additionally, large low-level vorticities also enhance development (Lin and Lee 2011).

Development parameters are varied and complex; therefore, there are only a few main development regions on the planet where the necessary conditions exist for cyclongenesis. These broad regions are mostly defined by SST, with smaller-scale fluctuations within each basin. Development regions, as stated previously, encompass 5°-25° on either side of the Equator. Thus, the North Atlantic/Gulf of Mexico region and the near-equatorial South Pacific are the main development regions affecting North America. The Indian and Pacific Ocean regions within the latitudinal bounds represent the other main development regions on a global scale. Figure 1.1 displays the main development regions, with generalized storm tracks for each region (Needham and Keim 2011).
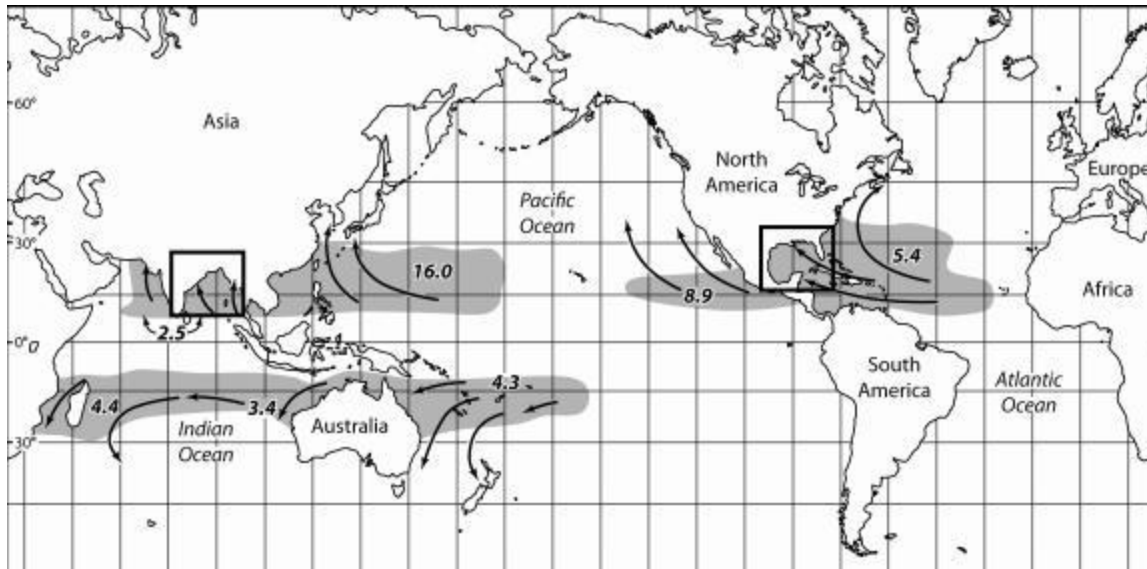
Figure 1.1: Main development regions for tropical cyclones on a global scale, depicted by gray shading. Generalized storm tracks depicted by heavy black arrows, and average number of tropical cyclones > 33 m/s (hurricane strength) provided by numbers in each zone. From Needham and Keim (2011).

After a tropical cyclone has developed, atmospheric dynamics are responsible for steering the storm. Each basin contains a generalized circulation pattern that governs tropical cyclone tracking. Both the North Atlantic and North Pacific are home to persistent high pressure cells - the Bermuda and Pacific Highs, respectively. The associated clockwise movement of air around these cells steers storms up the ACUS as well as into Eastern Asia. The cold air streams combined with cold ocean currents on the east side of the basins inhibits storm from tracking up the west coast of the United States as well as towards Africa and the Iberian Peninsula in Europe. The climatology of low pressure cells combines with easterly trade winds at these latitudes to steer storms from east to west, with a general curve northward as the system approaches landmasses and associated warm, northerly ocean currents.

Tropical cyclones threatening land are influenced by other variables. Coastline shape plays an important role in determining spatial distribution of landfalling tropical cyclones. Keim

et al. (2007) found that convex areas tend to have a higher number of tropical cyclones, while convex coastlines tend to be sheltered from storms (Figure 1.2). Tropical cyclones in the north Atlantic Ocean are influenced by the strength of the Bermuda High, a permanent region of high pressure roughly centered over the island nation of Bermuda. The clockwise flow around this high steers tropical cyclones in the Atlantic. In general, storms begin tracking westward with the trade winds around the bottom of the high pressure cell. Eventually, the storms begin a northward and finally northeastward track around the high (Davis et al. 1997). This gives Atlantic hurricanes their general tracking characteristics.

The Bermuda High is not a stationary phenomenon, however. Some years, the cell is located further to the east. In these years, most hurricanes are forced to recurve to the north before interacting with the ACUS. In other years, the cell is located further to the west, resulting in an increase in tropical cyclones making landfall along the ACUS. In still other years, the cell is located in its furthest west position, steering storms into the Gulf of Mexico (Davis et al. 1997). If the Bermuda High brings storms close the ACUS, the convex shape found in the southern part of the region becomes important. Storms first encounter south Florida, as it protrudes into the Atlantic Ocean more than any other part of the region. If a storm does not make landfall in south Florida, the Bermuda High tends to steer it to the north-northeast while remaining offshore, as the coast is convexly shaped. Storms tend to make landfall southern North Carolina, as this represents the region where the coast begins to protrude out into the Atlantic again. This pattern is also partly responsible for the lack of landfalling tropical cyclones in the Virginia and Chesapeake regions, as storms that would make landfall in these areas instead interact with the Carolinas.
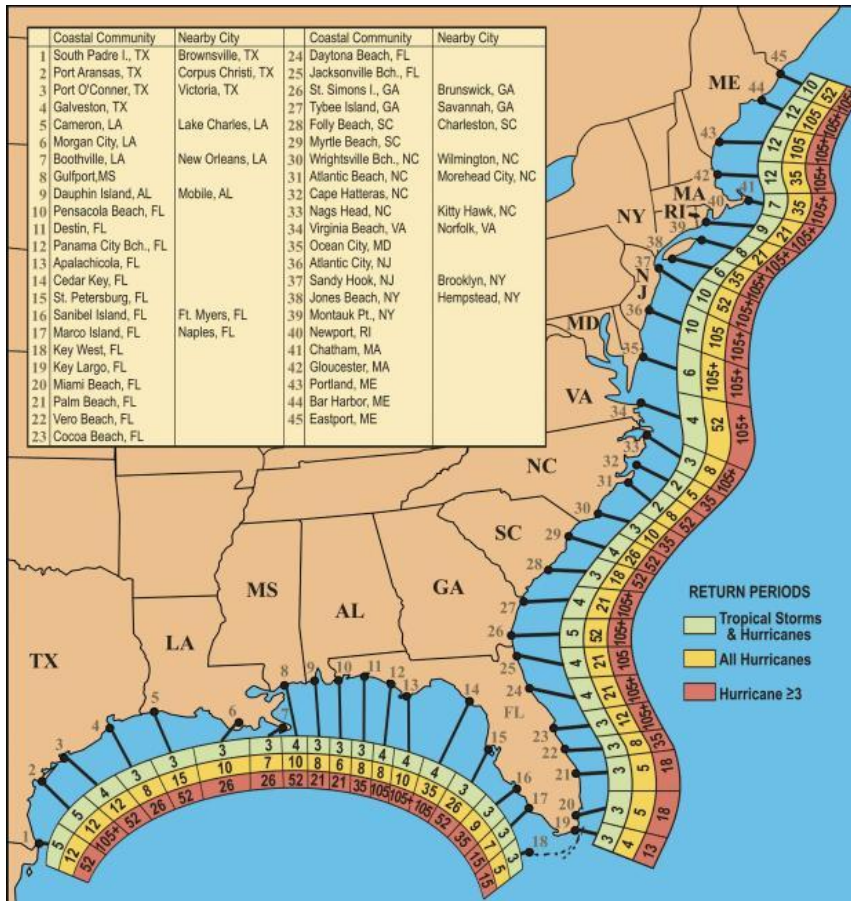
Figure 1.2: Spatiotemporal distribution of hurricane landfalls in the United States. Areas that jut out from the coast (South Florida, North Carolina, Louisiana Delta) tend to have more frequent storm landfalls versus convex regions (Georgia, Big Bend of Florida). From Keim et al. (2007).

1.2.3 Surge Formation Factors

As a tropical cyclone begins its approach towards land, storm surge begins interacting with the coastal environment. Surge generation does not follow one set of rigid guidelines; rather, an aggregation of several factors determines the surge at a given location. Maximum sustained winds, size and forward speed of the storm, coastline characteristics (shape and bathymetry) and tidal ranges play important roles in determining storm surge magnitudes.

1.2.3.a Wind Speed

The most basic determinant of surge is maximum sustained wind. It has been determined that wind stress tangential to the ocean surface determines 80-85% of storm surge in a given storm (Kurian et al. 2009). Winds are not uniform throughout a tropical cyclone, however. For strong storms, strongest winds tend to occur in the right front quadrant, while for weaker storms, the right rear quadrant tends to have strongest winds (Bell and Ray 2004). Additionally, the inclination of the storm to the coast at landfall also plays a key role. For example, if Hurricane Floyd (1999) had made landfall while its wind field was rotated – that is, at a different point in its counter-clockwise spin – maximum surge heights could have been 38% higher. A change in orientation of Floyd may have also caused a 50% decrease in negative surge, or a retreating surge caused by offshore winds (Xie et al. 2011). These results indicate that a significant portion of storm surge for a given storm is left to chance; although wind speeds are known in advance, orientation of landfall is not a variable that can be accurately predicted until the storm is close to making landfall.

1.2.3.b Physical Size

Irish et al. (2008) indicates that the physical size of the storm also influences storm surge. Results indicate that larger storms produce larger surges, especially when the storm is above Category 3. In 2004, Hurricane Charley rapidly strengthened from Category 2 to Category 5 strength in the 18 hours before landfall near Tampa, FL. However, a measurement of Charley's hurricane force wind field through data provided by the Atlantic Oceanographic and Meteorological Laboratory (AOML 2004) revealed a swath of only about 60 miles. The small wind field was one of the factors responsible for a surge that measured far below what one would

typically expect from a Category 5 storm. On the other hand, Hurricane Ike (2008) struck east

Texas as a Category 2 storm, but had a hurricane force wind field more than double Charley's,

(from AOML, following Powell et al. (1998) guidelines) and produced a devastating surge of

close to 6.1 m (20 ft) (Needham 2010). In light of the fact that both storms were of roughly equal

strength until just before landfall, but Ike had a much larger wind field, one can conclude that the

size of the wind field had at least some effect on the surge associated with these storms.

1.2.3.c Translation Speed

Translation speed exerts influence on surge, although the magnitude and direction of the

influence is still not fully understood. Rego and Li (2009) found that, as translation speed

increased, surge heights increased while inundation areas decreased in a study focused on the

Louisiana coast. Translation model results from the Atlantic coast, though, have yielded

contradictory results. A study investigating translation speed on the North Carolina coast showed

an almost perfectly linear increase in surge heights as translation speed decreased, with a less

clear trend for inundation area (Peng et al. 2004). The same researchers ran a similar model for

Charleston Harbor, SC. For this environment, the relationship between translation speed and

inundation area clearly indicates that slower storms produce larger inundation areas. The

relationship between translation speed and surge height is not as clear, though in 8 of the 12

model scenarios, surge increased as translation speed decreased (Table 1.1) (Peng et al. 2006).

The two Atlantic studies may be more relevant to the scope of this paper, suggesting that a

slower translation speed results in an increase in surge height and inundation. It is clear, though,

that translation speed alone cannot determine surge, though it does play a role.

Table 1.1: Model results of storm surge (SS) and inundation area (IA) for two storms with different translation speeds but identical physical characteristics, based on a variety of tracks. Both storms have a central pressure of 940mb, and a radius of maximum winds of 50km. Storm A has a forward speed of 36.5 km/hr; Storm B has a forward speed of 18.25 km/hr. Table adopted from Peng et al. (2006).

Track	Storm A		Storm B	
	SS	IA	SS	IA
1	5.14	105.73	4.96	144.2
2	4.76	105.04	4.77	144.98
3	2.99	59.7	3.31	103.17
4	2.09	11.66	2.23	48.4
5	2.36	44.92	2.46	53.41
6	4.53	129.45	4.18	143.57
7	5.03	127.15	5.01	155.02
8	0.69	0	0.95	0
9	5.56	119.78	5.43	164.97
10	5.35	121.13	5.75	167.26
11	4.37	90.16	4.4	128.07
12	2.31	7.09	2.64	29.51

1.2.3.d Bathymetry

As a storm and its associated surge approach the coast, it begins to interact with the bathymetry of the nearshore environment. This interaction has an effect on surge. When a storm is over open water, underwater currents can mitigate storm surge by carrying away bottom water and compensating for a piling up of water at the surface. Interaction with the sea floor as the storm nears the coast removes the bottom current, which generally results in increasing wave heights and water level at the surface (Rappaport and Fernandez-Partagas 1995). These findings were verified by Chen et al. (2008), who found that gently sloping, shallow coasts have the potential to produce higher surges than deep coasts. Thus, the earlier a storm interacts with the sea floor, the higher surges will likely be at landfall, as the storm has time to generate a high

surge. The influence of perturbations in nearshore bathymetry was examined, and found to

generally have a less than 10% influence on storm surge elevation at the shoreline. The same

study also found that the majority of bathymetric influences occur where depth is less than 30m;

beyond this, influence was muted (Weaver and Slinn 2010).

1.2.3.e Tidal Processes

Storm surge is a measure of the height of a water column above normal conditions. The

factors discussed above determine the height of storm surge above normal levels. However, the

timing of the storm's landfall plays a significant role in some regions. A storm making landfall at

high tide will have a higher storm surge reading than an identical storm making landfall at low

tide. Every coastal location experiences a tidal range; however, the difference between high tide

and low tide, or the tidal range, varies greatly from location to location. In the ACUS, for

example, tidal range varies from roughly 0.30 m at the Florida Keys to 5.5 m in Maine (Flick et

al 2003). Related research on the Gulf of Mexico largely ignored the influence of tidal ranges,

because ranges in this region tend to be small and mostly negligible – for example, Biloxi, MS

has a maximum range of 0.9 m at spring tide, but for much of the monthly tide cycle, ranges are

less than 0.5 m (Calvert 2004).

A seminal study on Atlantic tide ranges discovered a nearly linear correlation between

tidal range and continental shelf width (Redfield 1958). A strong correlation was found between

tidal ranges and distance to the 1000 m bathymetric contour. This is one explanation of large

Atlantic tidal ranges, but not the sole determining factor. Embayments tend to amplify the tidal

range, creating locally high ranges (Woodroffe 2002). Coastline shape plays a role as well, with

convex regions experiencing a funneling of tides toward the center of the formation, which is

influenced by angle of approach. Although these regions are normally sheltered from storms due to their orientation, they may see higher tides than one would expect should a storm approach the region.

1.3 Surge Impacts

1.3.1 Introduction

Storm surge is, by a variety of different measures, the deadliest component of a tropical cyclone. The American Meteorological Society placed the proportion of surge-related deaths associated with tropical cyclones at 90% of total US deaths through 1973 (AMS 1973). A follow-up study by Rappaport (2000) found the storm surge percentages to be lower than the AMS values from 1970-2000; however, the author notes this is likely due to small sample size, and that one large storm with a high number of surge deaths may restore surge as the number one killer. This period also corresponds with a general decrease in basin-wide storms, which may further skew results. Ali (1996) notes that storm surge is also the number one killer in the Bay of Bengal, India. In the south Pacific Ocean, De Scally (2008) notes that a single tropical cyclone once killed 1,000-2,000 people in the Cook Islands, with storm surge playing a major role in this death count. Additionally, surge events may lead to starvation and disease in these vulnerable island nations, introducing another aspect of sure devastation (De Scally 2008). On a global scale, storm surge represents the most dangerous threat to the lives of those in the path of a tropical cyclone.

1.3.2 Spatial Variability of Impacts

The ACUS represents a diverse geographic area, with different surge vulnerabilities in different locations. Two areas that present unique vulnerabilities to surge are the barrier islands,

such as the Outer Banks of North Carolina, and large urban areas, such as New York City. Both situations will now be examined.

1.3.2.a Barrier Islands

Barrier islands are uniquely vulnerable to tropical cyclones, and especially storm surge. These islands are generally narrow, and easily eroded by wind and surge events. Wang and Horowitz (2006) studied the effects of Hurricane Frances (2004) and Hurricane Jeanne (2005), both of which made landfall at a similar location in south Florida in consecutive years. The study examined the barrier island washover that occurred in the vicinity of landfall, and found that washover penetrated deep into the mangroves on the land-facing side of the islands. Over time, these washover processes migrate the island landward and may result in complete erosion of the landform.

Perhaps the most famous barrier islands along the ACUS are the Outer Banks of North Carolina, which are a historically active area for tropical cyclones. The Outer Banks are a series of narrow barrier islands off the northern North Carolina coast. (Figure 1.3) They are separated from each other by a series of inlets, which have historically undergone changes in response to tropical cyclone landfalls, with this change driven by surge events and associated erosion (Seneca 1972). Like most barrier islands, the Outer Banks are characterized by the presence of dunes. The large foredunes are particularly pertinent to storm surge inundations, because they shield the communities behind them from surge (Houser et al. 2008). Though these foredunes are a useful defense against surge, the rebuilding process after a surge event can be long. While the dunes are recovering, the island becomes extremely susceptible to surge. An example of this in a different location is 1983's Hurricane Alicia, which made landfall near Galveston Texas, a

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barrier island environment on the Gulf Coast. Three years prior, Hurricane Allen impacted this

region, eroding foredunes and causing erosion. As a result, Hurricane Alicia's surge was

magnified and more devastating in this area due to the lack of protective foredunes (Houser et al.

2008).The southern portion of the Outer Banks see a major hurricane (Category >3) once per 35

years, on average (Keim et al. 2007). This puts these barrier islands in serious jeopardy of

suffering extensive erosion, and possibly even eradication should a number of strong storms

impact the islands over a short period of time.
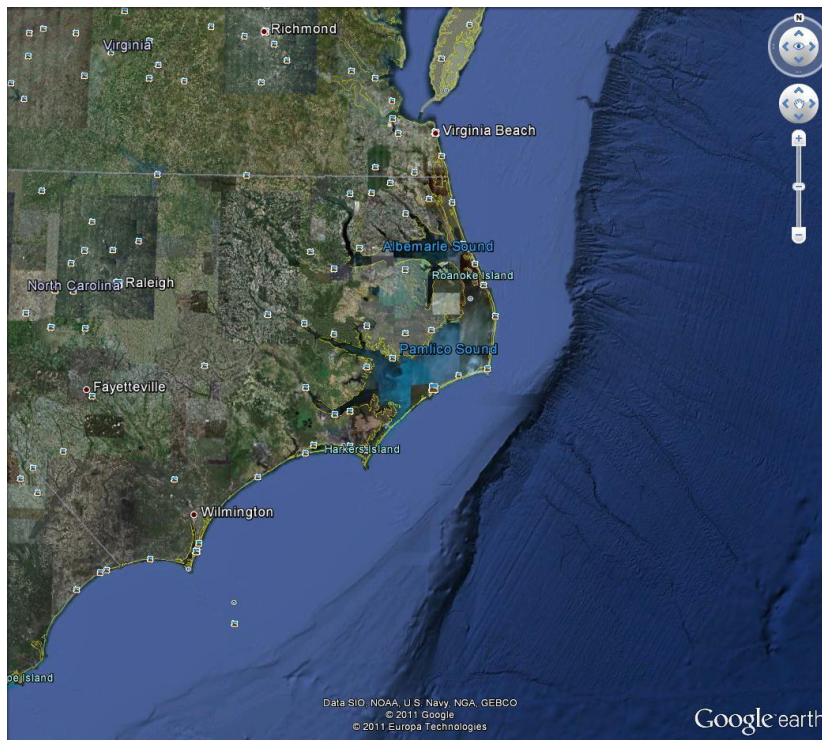
Figure 1.3: Location of the Outer Banks of North Carolina within the state of North Carolina. The Outer Banks are the chain of barrier islands separating Pamlico and Albemarie Sounds from the Atlantic Ocean.

1.3.2.b Large Urban Areas

Large urban areas represent a much different type of vulnerability to surge events. These

locations are home to millions of people, and if the city is located along the shoreline, an

inherent storm surge risk emerges. Evacuation of millions in a short time period poses a serious

logistical issue. In the event that residents choose to remain and ride out the storm in a multiple-story building, the residual surge damage, though not deadly, would prove to be a serious disruption and threat to the existing built infrastructure.

New York City is perhaps the most uniquely vulnerable large urban location to storm surge. The island of Manhattan alone is home to over 1.5 million residents. Each of these residents relies on infrastructure that would be compromised by a large surge event, especially those infratructures that exist beneath street level. Historically, the metro area has escaped the wrath of most tropical cyclones tracking up the Atlantic; most of the city's historical surge events resulted from winter Nor'easters (Colle et al. 2010). The highest surge event in Manhattan from 1959-2007 was 2.10 m, associated with Hurricane Gloria in 1985. This is relatively modest surge, though the dense urban network of New York City exacerbates impacts. A 2.10 m surge in New York City is likely to cause more disruptions and damage than a similar surge in less populated built environments, such as the Georgia coast.

Although the city has escaped major disaster to this point, projected sea level rise presents potentially devastating consequences. Colle et al. (2010) used incremental sea level rises of 12.5, 25 and 50 cm, in accordance with the Intergovernmental Panel on Climate Change's Fourth Assessment Report's projections for 21st century rise. Results show a substantial increase in surge events as sea level increases. For example, the ten year period of 1997-2007 contained zero events that the authors classify as 'moderate' (surge > 1.0 m). When sea level is raised by 13 cm, 25 cm and 50 cm, the number of moderate surge events from 1997-2007 jumps to 4, 16 and 136 events, respectively. This increase is to be expected, as a higher baseline sea level results in a higher level of inundation in the urban environment. Results of this study show that

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New York City can expect to see an increase in frequency and magnitude of surge events in the coming century.
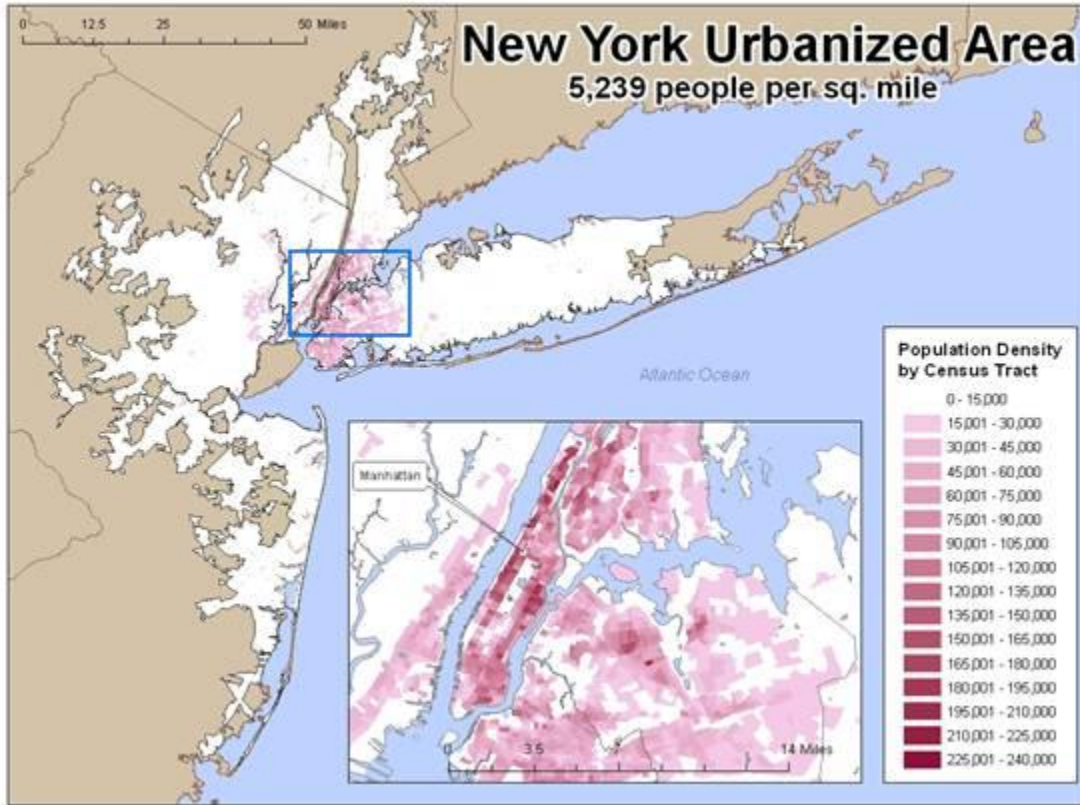
Figure 1.4: Population density map of New York City, with Manhattan in inset. The high population density of New York City may result in difficulties in evacuation associated with an approaching tropical cyclone.

Comparing these two coastal locations provides context for the spatial variability of vulnerability to storm surge. Barrier islands and other exposed coastal locations are at risk of migrating landward, losing surface area or vanishing completely, while urban areas are susceptible to greater devastation from a relatively small event due to their dense nature and potential evacuation issues. Later chapters of this thesis will investigate spatial vulnerability to storm surge, and determine areas that are most vulnerable to surge events.

1.4 Conclusion

Although storm surge produces the most fatalities and monetary damage of tropical cyclone-associated hazards, the processes that produce surge are dynamic. It is difficult to accurately predict the height of storm surge very far in advance. Timing of landfall with respect to tidal cycles, bathymetry of the coast, exact landfall position and other factors exert influence on the surge, and are difficult to quantify and model. In addition, vulnerabilities to storm surge vary greatly from location to location. Barrier islands are amongst the most susceptible locations to storm surge. In addition to the Outer Banks, the ACUS features many other barrier islands; examples include Assateague Island in Maryland, Long Beach Island in New Jersey, and Jones Beach off the coast of Long Island in New York. Large, dense urban areas represent another unique vulnerability. New York City, though the largest urban area along the ACUS, is not the only dense urban environment. Miami, FL, Charleston, SC, Providence, RI and Boston, MA are four examples of areas with a large urban population. Given the large number of vulnerable areas to surge events, this paper intends to better determine spatial vulnerability of storm surge, and provides a clearer view of where large surge events can be expected on the ACUS.

CHAPTER 2: CREATION OF A STORM SURGE DATABASE FOR THE ATLANTIC COAST OF THE UNITED STATES

2.1 Introduction

Storm surge is a vital component of tropical cyclone vulnerability. At present, most storm surge information available to the scientific and general communities is in the form of model estimations of surge. An example of a surge modeling system is the National Hurricane Center's Sea, Lake and Overland Surges from Hurricanes (SLOSH) model. The SLOSH model uses the generating forces discussed in Section 1.2.3 to estimate potential maximum surge for a particular storm and location. The SLOSH model claims accuracy to within 20 percent; however, at times the model over-or-under-estimates the actual storm surge by a larger percentage. Needham (2010) discusses instances of such mis-estimations. ADCIRC is another example of a surge model currently in use. ADCIRC is a multi-dimensional model that uses highly flexible, unstructured grids to analyze phenomena such as storm surge, tidal processes and sediment transport. ADCIRC is extremely sophisticated; however, this sophistication requires the use of supercomputers and thus ADCIRC has limitations as far as ease of use is concerned.

Predictive models such as SLOSH and ADCIRC are useful to a certain extent; however, there is intrinsic value in a collection of observed, historical surge maxima. These observations can be compared to model outputs, and improvements can be made to the models based on these historical data. Access to a database of historical surge events has utility outside of the scientific community, as well. Coastal developers benefit from knowledge of past surge events, and can set architectural and other standards based on maximum inundation events of the past. Surge values and return periods provide guidance to insurance agencies in determining rates for landowners in

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coastal zones. Emergency management officials use frequency and extent of inundation events to design evacuation and response plans when faced with a landfalling storm. These represent only a cross-sampling of stakeholders benefitting from a centralization and analysis of inundation events.

In this chapter, methodologies for the creation of a storm surge database for the ACUS will be discussed. This chapter will also discuss various analyses performed on the data collected.

2.2 Database Creation

2.2.1 Criteria for Inclusion

Following the parameter established in Needham (2010), storms with a maximum inundation of 1.22 m (4 ft) are eligible for inclusion in the data set. This height was chosen because, at the start of the creation of SURGEDAT, 1.22 m was the "typical" storm surge associated with a Category 1 storm on the Saffir-Simpson scale. Although the scale has since been modified and no longer includes surge estimates, the parameter is employed in this research to keep consistency throughout SURGEDAT. This cutoff eases some of the burden of data collection. Storms producing a surge of less than 1.22 m are less likely to contain documentation of a surge height, as the damage associated with such a low surge is likely to be minimal. Thus, truncating the database at this surge height is warranted.

Hurricane "best track" information is available to the public dating back to 1851, as provided by the HURDAT project (Landsea et al. 2004). However, this project features a temporal range of 114 years, 1898-2011. The year 1898 was chosen as the start date for this dataset based on the available data. The sparse nature and potential unreliability of the record

before 1898 precludes the inclusion of storms from that time period. Although Landsea et al. (2004) claim that reliable tropical cyclone records have existed for most of the study area since at least 1851, storm surge information from early years in the HURDAT is not comprehensive, and surge data mining is difficult due to the age and accessibility of the data.

Because this project is an extension of previous work and part of a larger, global project, the ACUS was a logical geographic region for this study. Needham (2010) provided a comprehensive surge analysis for the Gulf of Mexico (GOM) coast, making progression up the Eastern Seaboard a natural one. This project will effectively complete storm surge analysis for the United States, due to the lack of surge events on the west coast and Hawai'i. The specific southern extent of the study range is defined in Needham (2010). The GOM study range had an eastern limit of County Road 905A, from Dagny Johnson Key Largo Hammock Botanical State Park to the Texas-Mexico border. Therefore, any storm making landfall between the Key Largo State Park boundary and the United States-Canada border in Maine is eligible for inclusion.

Storm track information for each storm from 1851-present is available on the web through the Unisys Weather Hurricane Data Website. Each year from 1898-present was examined for this study, and storms to be included in the database were chosen from this source. Storms that made landfall were the first to be included in the database. Storms that did not make landfall but came within a specific buffer of the coast were also included, as surge may have propogated towards land even though the storm did not make landfall. This buffer was determined in Keim et al. (2007). The authors determined extent of storm conditions for storms of various intensities. The modeled results are as follows: for tropical storms - tropical storm force winds extend 80 km to the right and 40 km to the left of center; for category 1-2 hurricanes – hurricane force winds extend 80 km to the right and 40 km to the left of center, with tropical

storm force winds extending another 80 km and 40 km, respectively; for major hurricanes (>category 3) – major hurricane force winds extend 80 km to the right and 40 km to the left of center, weak hurricane force winds extend 80 km and 40 km, respectively, and tropical storm force winds extend 80 km and 40 km, respectively (Figure 2.1). Using these parameters, any storms that passed within its respective buffer of the coast was included in the database.
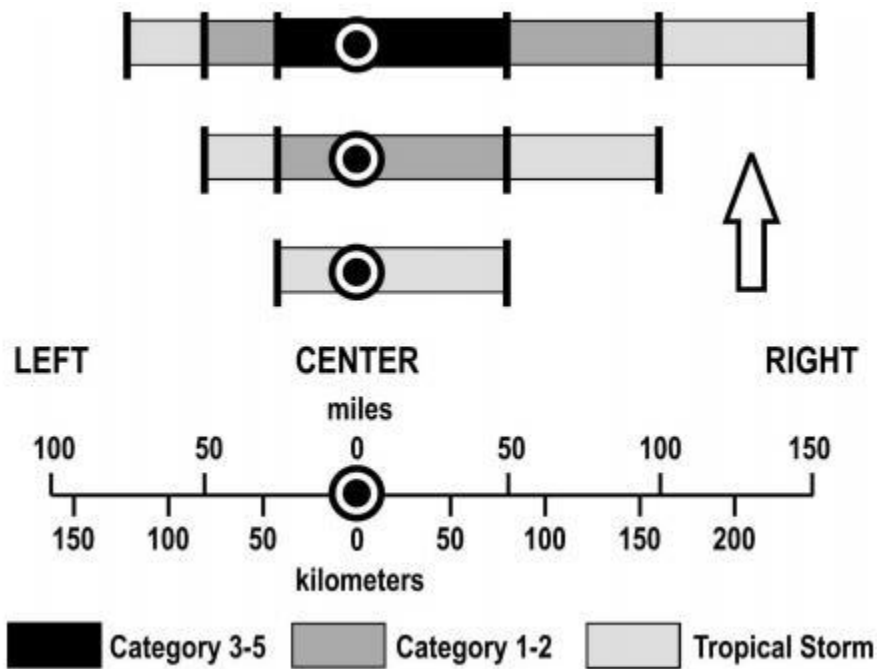
Figure 2.1: Modeled extent of wind fields for an average storm. Taken from Keim et al. (2007).

Once the criteria listed above were established, each storm that had the potential to produce a surge ≥ 1.22 m was listed in a metadata file. Storms were listed chronologically, and each storm contains the following information: name (where applicable), dates the storm was active, location, height and date of peak surge inundation, and a list of sources and relevant quotations/tables from the sources. In the next section, data collection methods used to acquire the necessary information will be explored.

2.2.2 Data Collection

Data collection presented the most time consuming challenge of this project. Due to the lack of a centralized storm surge database, an aggregation of many different sources into one complete data set provided a monumental challenge. The first data source used for this aggregation was the AOML's Monthly Weather Review Annual Summaries of North Atlantic Storms (MWR), a once-yearly product of the National Hurricane Center providing capsules of each of the previous season's storms. Prior to 1962, the MWR was almost exclusively qualitatively focused, with surge accounts embedded in text descriptions of storms. For example, a typical surge description reads similarly to this excerpt from the write-up on a November storm affecting Miami in 1935:

> "No reports of any extremely high tide in connection to this storm has been received. At Miami, a tide of 5ft, 2.2 ft above mean sea level was reported at 2PM, about 15 minutes after the passage of the calm center. At Pigeon Key in Biscayne Bay, an estimated reading of almost 6 ft was made. A high tide was reported at Fort Lauderdale following the axis of the storm center and wind shift from the northwest to easterly, but details are lacking." – November 1935 Monthly Weather Review, p. 317

Beginning in 1963, the MWR began listing a table of meteorological observations for each storm. Included in these tables are surge values for various coastal points, near the landfall region and beyond. Therefore, from 1963-2010, the MWR was an extremely helpful resource. Even in instances where the MWR was not the sole determinant of inundation, the spatial extent of surge values provided guidance as to where the highest tides did occur.

Another useful and electronically available resource published by the NHC is storm wallets. Storm wallets contain all meteorological observations and relevant observations related to a particular storm. Storm wallets for the ACUS are available beginning in 1958. Although much of the information presented in the storm wallets is accounted for through the

aforementioned MWR storm charts, there is additional information to be gained by reading the wallets. Wallets contain bulletins issued by the Weather Bureau/NWS in advance of, during, and after the storm's landfall. They provide valuable information such as tidal conditions at landfall as well as tides reported by ships off the coast. This information provides more context for surge events, and allows for a greater understanding of the dynamics associated with each individual storm. In scenarios where different sources provide different inundation values for a storm, this type of background knowledge helped guide estimates of storm surge.

Other electronic resources provided by the NHC and NOAA were utilized in the creation of the database. A review of Virginia's hurricane history from 1900-1949 produced by the NOAA's Hydrometeorological Prediction Center contained useful information for storms in that state. A special NOAA report commemorating the 50th anniversary of 1959's Hurricane Gracie contained relevant surge information for that particular storm. Outside of NOAA, the US Army Corps of Engineers also produced storm summaries for some storms, like Hurricane Hugo.

The next major contributor to the database was historical newspaper archives, stored as microfilms. For each storm in the database, the closest newspaper in publication at the time of landfall was ordered through Louisiana State University's Interlibrary Lending service. These newspapers were then analyzed through a microfilm scanning machine, and any relevant accounts of storm surge (quantitative or qualitative) or photographs of inundation or damage were scanned and digitally saved. Six newspapers were used for this process, covering almost the entire ACUS.

The last major component of surge aggregation was the use of books and encyclopedias, usually published through non-academic sources. A number of publications focusing on certain

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regions of the ACUS provided detailed storm accounts on a local scale. Two books of particular utility were authored by Jay Barnes – *Florida's Hurricane History* and *North Carolina's Hurricane History.* The texts are structured similarly, with detailed accounts of notable storm events in each state. These accounts contain anecdotal and measured data, both of which are used in determining surge events. Another book focusing on hurricanes in Florida, *Florida Hurricanes and Tropical Storms, 1871-2001* by John Williams, provided more insight into Florida storms, with pertinent information on surge heights. *Low Country Hurricanes* by Walter Fraser provided a detailed account of storms affecting the low country of South Carolina and Georgia. This book was particularly useful for storms in the first half of the database. This region was less developed than areas such as south Florida or the northeast at this time, so newspaper information was often scarce. This book therefore filled many voids in surge values.

The sources described above accounted for a majority of surge values; however, they do not represent a comprehensive list of sources. A comprehensive list of sources appears in Table 2.1

Table 2.1: List of sources used in creation of the storm surge database for the Atlantic Coast of the United States.

Newspapers	
Newspaper Title	**Location**
The Lewiston Daily Sun	Lewiston, ME
The Boston Globe	Boston, MA
The New York Times	New York, NY
The Winston-Salem Journal	Winston-Salem, NC
The Wilmington Morning Star	Wilmington, NC
The Miami Herald	Miami, FL

Table 2.1 continued
Books, Encyclopedias, Web Sites

Source	Publication Date
Jay Barnes, *Florida's Hurricane History*	2007
Jay Barnes, *North Carolina's Hurricane History*	1998
James Elsner, *Hurricanes of the North Atlantic: Climate and Society*	1999
Walter J Fraser, Jr., *Low Country Hurricanes*	2006
David Langshore, *Encyclopedia of Hurricanes, Typhoons and Cyclones*	2000
Scott Mandia, The Long Island Express (website)	Unknown
Unkown author, New Point Comfort (website)	2006
Jim Williams, Hurricane City (website)	Continually updated
John Williams, *Florida Hurricanes and Tropical Storms, 1871-2001*	2002

Government Documents

Source	Data Dates	Publication Date
D. Lee Harris, Characteristics of the Hurricane Storm Surge (Technical Paper No. 48)	1926-1961	1963
NOAA's *Monthly Weather Review*	1898-present	Current
National Hurricane Center, Archive of Hurricane Seasons	1958-present	Current
National Weather Service, Charleston, SC, *50th Anniverary of Hurricane Gracie*	1959	2009
Christopher Landsea, HURDAT Re-analysis	1898-1925	2009
Ed Rappaport, *Preliminary Report: Hurricane Andrew*	1992	1993
David Roth, *Virginia Hurricane History*, NOAA publication	1901-1999	2001
US Army Corps of Engineers, *Hurricane Hugo Assessment*	1989	1990
US Dept. of Commerce, *Hurricane Betsy: August 27-September 12,1965*	1965	1965
USGS, Hurricane Irene Storm Tide Mapper	2011	2011

2.2.3 Obtaining Surge Heights from Data

2.2.3.a Interpreting Different Surge Accounts

Ideally, some combination of available sources for a particular storm produced a reliable estimate of peak surge, especially when sources agreed. For storms in the latter part of the database, this was normally the case. Increases in coastal population as well as heightened awareness of the power of storm surge likely contributed to the clarity of surge records in the

past fifty years. It was fairly straightforward to acquire a concrete estimate of surge for these years.

In some cases, especially as one progresses back in time, surge is not expressed quantitatively. Commonly, surge was expressed similarly to this description of a late July, 1926 Florida hurricane from Williams (2002):

> "The high winds and seas swept before them boats, docks, boat houses and other marine property on the ocean front as well as that on the Indian River Lagoon….the observer at Merritt Island remarks that there was a tremendous wave and with the high wind all boats, docks and other property from the river front were swept ashore." – p. 110

In these instances, obtaining surge heights becomes more of an art than an exact science. Google Earth provides elevation above sea level for every point on the Earth's surface. For this particular storm, Google Earth reveals a sharp rise in elevation to 8 ft very close to the river front on Merritt Island. The steep gradient leads one to believe that, for boats and other property to be described as being "swept ashore," they likely reached this 8 ft level. This information, and the fact that this was a Category 2 storm at landfall that had previously been stronger, led to a classification of this event as an 8 ft surge. It should be noted that although the description is for a river tide, the river is separated from the lagoon and ocean by only a small stretch of land (Merritt Island), and the tide is likely accurate. For a map of the region in question, see Figure 2.2.

Different source accounts of the same storm did not always yield the same surge estimate. In these instances, a best estimate of surge height was made based on available information on the geography of the coast and storm track. Hurricane Diane (1955) is an example of such a storm. From Barnes' *(1998):*

"But as with Connie, Diane's wind drive tides and torrential rains brought extensive flooding to the Tar Heel coast. Tides associated with Diane were generally higher than those of the previous hurricane and ranged from five to nine feet above mean low water along the beaches." – p. 111-112

From the same storm, the *Wilmington Morning Star* reports:

"Hurricane Diane, swirling 135 MPH winds around its eye, slammed into North Carolina's southeastern coast Tuesday night with torrential rain and tree bending winds that threatened to push tide to 12 feet above normal.....the hurricane's surge of tide was expected to coincide with a full moon high tide. (9/12/1955)"… "The two front streets of Long Beach were under 4 feet of water. (9/13/1955)"

The first clue to the true surge of this storm comes from the revelation that the storm was expected to coincide with a full moon high tide. In actuality, the storm made landfall later than anticipated, and did not coincide with high tide. Thus, the 12 foot prediction is likely too high. The next piece of relevant information is the flooding of Long Beach beachfront streets. A USGS 15" Topographic map places the two front streets in Long Beach at roughly 3 ft above sea level. Four feet of flooding on a street three feet above sea level results in a tide of at least 7 ft in this location. Seven feet is squarely in the middle of Barnes' (1998) estimation. However, the description of the tide as "generally higher than those of the previous hurricane" (Barnes 1998) results in an upward adjustment of the surge value. The previous storm (Hurricane Connie) has multiple accounts corroborating a seven-to-eight foot surge. Therefore, the value of this surge event was placed at nine feet.

These methods have some inherent dangers. Different coastal locations that are relatively close to each other may have drastically different heights of roadways, for example. In cases where the landfalling location is not identified by a street name or landmark (such as a hotel or restaurant), some degree of estimation is required to place the surge in a particular location. In general, though, coastal areas seem to be relatively uniform in elevation, especially barrier islands, which is where many anecdotal accounts originate from. This estimation technique is far

from perfect; however, given the ease and relative reliability of elevations provided by Google

Earth and the USGS Topographic maps, this technique produces relatively sound estimations.
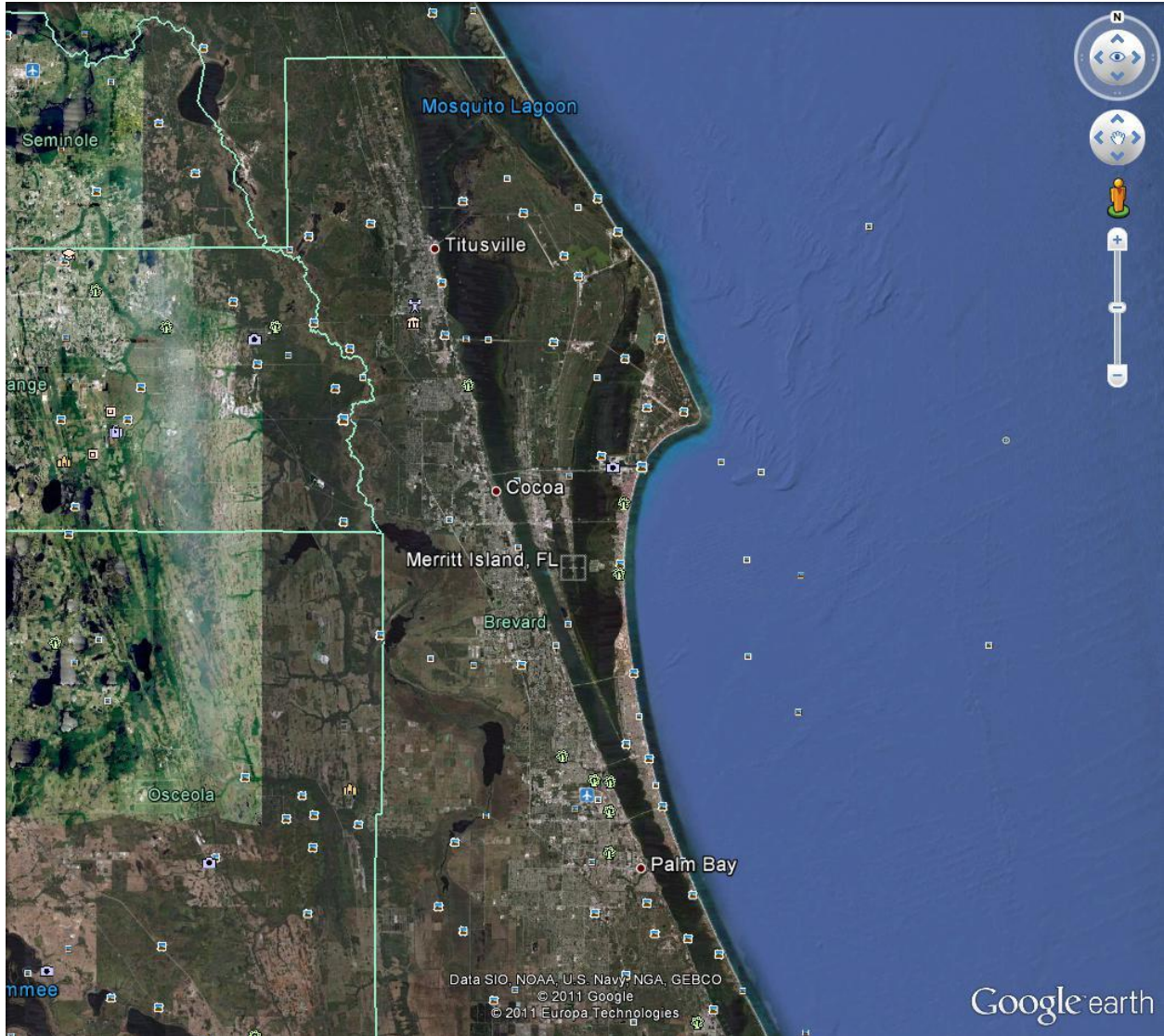
Figure 2.2: Merritt Island, FL, represented by the box with crosshairs in the center of the map. Merritt Island is one location that required the use of Google Earth to determine surge heights. Image taken from Google Earth.

2.2.3.b Tidal Adjustments

Storm surge is, by definition, an abnormal variation in sea surface height due to external

forcings, such as that provided by a tropical cyclone (Flather 2001). The phrase 'abnormal

variation' is the keystone of surge measurement and recording. Every coastal location has a background tidal profile, with tide rising and falling harmonically throughout the day. To obtain an accurate representation of the abnormalities in surface height due to an approaching tropical cyclone, one must account for the normal astronomical tide. In the second half of this data set (1960-present), improvements in tidal measurements, extensive observation networks and other technological advances result in surge values that are usually represented as height above astronomical tide. These data are included in the metadata without necessitating an adjustment for tides.

Progressing back in time, surge accounts become more anecdotal, and numerical accounts are often given as "above mean low water." This type of account does not provide any insight into tidal influences and landfall. On occasion, surge accounts will mention the tidal activity at landfall qualitatively, but not numerically. An example is 1954's Hurricane Hazel. From Barnes (1998):

> "The storm surge that Hazel delivered to the southern beaches was the greatest in North Carolina's recorded history. The flood reached eighteen feet above mean low water at Calabash. Hazel's surge was made worse by a matter of pure coincidence - it had struck at the exact time of the highest lunar tide of the year - the full moon of October"- p. 83

Hazel's surge was boosted by the timing of its approach. However, it is not enough to know that the surge occurred at high tide. To provide an accurate representation of the storm surge and ensure that all data are adjusted to the same parameter, it is necessary to adjust surge accounts that do not account for astronomical tide.

These corrections were applied through software provided by the Nobletec corporation called Tides and Currents. This program provides continuous tidal cycles for hundreds of coastal locations dating back to 1901. A file was created containing all storms requiring tidal correction.

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For some storms, an exact time of landfall was given in the metadata; however, for the majority, no such information exists. In these cases, UNISYS track data were used, and time estimates were obtained through these storm tracks. Date, approximate time, point of impact and storm surge were placed in the storm file for analysis. For the majority of storms, the point of impact was represented with a gauge in the Tides and Currents software. In these instances, the date of landfall was entered into the program, and astronomical tide associated with the surge timing was ascertained. These values were then subtracted (or added, if at low tide) from the metadata surge values, and the result was the amount of anomalous water rise associated with the tropical cyclone, or true surge.

The tidal adjustment was straightforward for most surge events. However, in a few instances, the point of impact was not represented with a gauge in the Tides and Currents program. In these cases, a normalization process was applied to determine tidal ranges at the required location. Working under the assumption that tidal ranges and heights do not fluctuate substantially on a centennial time scale, a transformation was applied. First, the nearest gauge in the software package to the impact point was determined. Next, present tidal ranges (timing and magnitude) were found for both locations. For the gauge represented in the software, this information came from the program itself. For the surge location, tidal information was obtained from several different websites containing tidal information. To ensure accuracy, data from several different tidal websites were cross-checked against one another. As another quality control check, tidal information for sites given in the software were compared to values obtained from the Internet. In each case, the web values and the values obtained from the program were equal, thus confirming the reliability of these measurements. Once the data were found, the time and height of high and low tides for each location were entered into a spreadsheet. Three days of

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information were logged for each location. To determine the relationship between stations, the information was analyzed to determine timing and magnitude differences. Timing differences between high tides were recorded and averaged, and the same was done for low tides. The same process was applied to tidal heights. With these calculations, tidal conditions can be determined for locations that are not represented in the software. An example of this process follows.

On September 16, 1928, the so-called Okeechobee Hurricane made landfall in south Florida. Data collection placed the maximum surge of 12 ft at 2:30 PM at Palm Beach, FL. Palm Beach is not represented in Tides and Currents; the nearest gauge is Lake Worth Pier, approximately 8 miles to the south. Analysis of tides showed that, at present, Palm Beach lags Lake Worth Pier by 35 minutes at both high and low tide, and heights are identical. That is, a high tide affecting Lake Worth Pier at 2:00 AM with 2 ft waves will affect Palm Beach at 2:35 AM with 2 ft waves. Because the lag time is identical, it is reasonable to assume that Palm Beach lags Lake Worth Pier by 35 minutes at all times. Thus, to find the tide at 2:30 PM at Palm Beach, one must identify the tide at 1:55 PM at Lake Worth Pier. This tide is 1.5 ft. Therefore, the 2:30 PM tide at Palm Beach was also 1.5 ft. Removing this from the original 12 ft value results in a true storm surge of 10.5 ft at Palm Beach, FL.

This tidal adjustment represents the first attempt to remove the tidal component of storm surge values on a scale this large. This technique is applicable to areas beyond the ACUS, as long as tidal information can be obtained for the site in question. Future research will apply this tidal correction to all other necessary events in SURGEDAT, thus creating an accurate representation of pure storm surge. This process will create a homogenous dataset, with each surge event representing the anomalous rise of water associated with a tropical cyclone rather than the total water height.

2.2.4 Omission of Storms

When the framework of the database was initially created (Section 2.2.1), many small tropical storm and minimal hurricane events from the very early part of the 20th century were included. Every effort was put forth to track down relevant surge information for every storm. The spottiness of recorded observations and the minor nature of many of these small events resulted in an omission of a fair number of events in the early part of the record. This creates an inhomogenous dataset through time. Although most large events from this period contained ample surge information, surge events that were relatively minor but still large enough to be included in the database (>1.22 m) were often not noted in newspaper accounts from this time period, due to the lack of damage inflicted and many times a lack of population in the landfalling area. As time progresses, the surge record becomes more comprehensive, so that a similarly minor surge event from the late 20th/early 21st century is likely to have a surge observation. These inconsistencies are not ideal; they are, however, an inherent difficulty in working with historical data, and it is difficult to avoid such omissions.

2.3 Conclusion

Creation of a storm surge database and centralization of data from a variety of sources is a tedious process that requires knowledge of coastal geography as well as general cyclonic surge characteristics. Extensive data mining resulted in enough data to produce peak surge estimations for many tropical cyclone events affecting the ACUS. Most major storm events are accounted for in this dataset. There are some larger storms missing that may influence further analysis if they are considered. An example is the August 4, 1933 tropical cyclone that made landfall north of Jupiter, FL. This storm had winds of 120 MPH at landfall, making a Category 4 storm that likely

produced a significant surge event. However, the rural nature of the landfall region at the time precludes any quantitative or qualitative surge account from appearing in the record. This storm represents the only major hurricane missing from the dataset; all other omitted storms are of tropical storm or weak (Category 1) hurricane intensity, and likely did not produce a large enough surge to significantly skew data analyses.

In spite of these missing events, enough surge records were found to run data analysis. A complete listing of surge events contained in this dataset can be found in Table 2.2. A master list of surge events allows for a variety of analyses to be performed, and conclusions to be drawn about trends and spatial variability of surge events along the ACUS. The next two chapters of this thesis contain these analyses and results.

Table 2.2: Master list of all tropical cyclones producing a storm surge ≥ 1.22 m (4 ft) for the Atlantic Coast of the United States, 1898-2011.

Date	Location	Name	Surge (m)
10/1/1898	Sapelo Island, GA		5.49
8/17/1899	Hatteras, NC	San Ciriaco	2.44
9/11/1903	Jupiter, FL		1.52
9/17/1903	The Battery, NYC	Vagabond	1.95
10/18/1906	St Augustine, FL		2.43
8/27/1911	Charleston, SC		1.80
9/17/1914	St Augustine, FL		1.52
8/25/1918	Lumina, NC		2.47
9/18/1926	Coconut Grove, FL	Great Miami	3.75
9/28/1926	Merritt Island, FL		2.26
9/16/1928	Palm Beach, FL	Okeechobee	3.41
8/8/1928	Ft. Pierce, FL		3.35
8/23/1933	Sewells Point, VA	Chesapeake-Potomac	2.53
9/16/1933	Sewells Point, VA		2.99
5/29/1934	Beaufort, SC		1.22
11/4/1935	Fort Lauderdale, FL		2.13
9/18/1936	Sewells Point, VA		2.83
9/21/1938	Fairhaven, MA	Great New England	6.49
8/11/1940	Lady's Island, SC		3.44
9/15/1944	Providence, RI		3.20
10/19/1944	Jacksonville Beach, FL		3.23
9/17/1945	Cutler Ridge, FL		3.66
9/17/1947	Boca Raton, FL	George	2.29
10/15/1947	Parris Island, SC		3.17
8/27/1949	Palm Beach, FL	Delray Beach	2.10
10/18/1950	Miami Beach, FL	King	1.52
8/15/1953	New Bern, NC	Barbara	1.83
8/31/1954	Bristol, RI	Carol	2.99
10/15/1954	Atlantic Beach, NC	Hazel	4.54
8/12/1955	Fort Macon, NC	Connie	1.65
8/19/1955	Long Beach, NC	Diane	2.74
9/19/1955	New Bern, NC	Ione	3.23
9/27/1956	Sewells Point, VA	Flossy	1.34
9/27/1958	Hatteras, NC	Helene	1.31
7/9/1959	Bulls Bay/McLellanville, SC	Cindy	1.22

Table 2.2 continued

9/16/1959	Jeremy Inlet, SC	Gracie	3.05
9/12/1960	Atlantic Beach, NC	Donna	2.19
9/27/1964	Pompano Beach, FL	Cleo	1.83
9/10/1964	Anastasia Island, FL	Dora	3.66
9/8/1965	Miami Beach, FL	Betsy	1.52
9/15/1967	Indian River Inlet, DE	Doria	1.71
10/20/1968	Wilmington, NC	Gladys	1.52
8/28/1971	Providence, RI	Doria	1.25
10/1/1971	Atlantic Beach, NC	Ginger	1.22
8/10/1976	Manhattan	Belle	1.37
9/4/1979	Tybee Island, GA	David	3.78
9/14/1984	Carolina Beach, NC	Diane	1.68
9/27/1985	Battery Park, NYC	Gloria	2.10
8/19/1986	Nantucket, MA	Charley	1.22
9/22/1989	Bulls Bay, SC	Hugo	6.10
8/19/1991	Willets Pt, Queens, NY	Bob	2.13
8/24/1992	Biscayne Bay, FL	Andrew	5.15
9/26/1992	Hatteras, NC	Danielle	1.65
8/31/1993	Buxton, NC	Emily	2.99
6/18/1996	Cape Lookout, NC	Arthur	1.74
7/12/1996	Topsail Beach, NC	Bertha	2.74
9/2/1996	Nantucket, MA	Edouard	1.22
9/6/1996	Figure Eight Island, NC	Fran	3.66
8/28/1998	Coastal Pasquotank, NC	Bonnie	1.83
8/30/1999	Oriental, NC	Dennis	2.41
9/17/1999	Oak Island, NC	Floyd	2.04
9/11/2002	Dare, NC	Gustav	1.68
9/18/2003	Smithfield, VA	Isabell	3.28
8/3/2004	Buxton, NC	Alex	1.83
9/14/2004	Long Beach, NC	Charley	2.29
9/29/2004	Bulls Bay, SC	Gaston	1.37
9/5/2004	Vero Beach, FL	Frances	2.44
9/26/2004	melbourne, FL	Jeanne	1.83
9/15/2005	Onslow Beach, NC	Ophelia	1.52
9/8/2008	Wilmington, NC	Hanna	1.52
9/3/2010	Hatteras Village, NC	Earl	1.31
8/28/2011	Long Beach, NY	Irene	2.16

CHAPTER 3: SPATIAL, TEMPORAL AND STATISTICAL ANALYSIS OF STORM SURGE

3.1 Introduction

Tropical cyclones pose a significant threat to the lives and livelihoods of coastal residents. Although better preparation, warning systems and knowledge of hazards associated with tropical cyclones have decreased hurricane mortality rates over the past century, vulnerability is still substantial (Willoughby 2012). Hurricane Katrina provides an example of the still-present risk. Willoughby (2012) found that in spite of decreasing trends, one major event (such as Katrina) has reversed the expected loss of life and damage trends.

The example of Hurricane Katrina illustrates the dangers of tropical cyclone hazards, and in particular storm surge. New Orleans is perhaps the most vulnerable city in the country to surge, as large portions of the city are below sea level (USGS 2005). Although most coastal communities along the Atlantic Coast of the United States (ACUS) are at least at sea level, storm surge still carries considerable risk to lives and livelihoods. Despite these major risks, storm surge is, at present, a relatively under-reasearched field in the study of tropical cyclones. An increased understanding of surge characteristics such as spatial variability and climatological factors that promote an increase in surge heights is of utmost importance to emergency management planners, coastal zone managers, homeowners, law enforcement units and countless other stakeholders.

This chapter seeks to discover some of the spatial, temporal and statistical characteristics of storm surge. Similar studies have linked all of these characteristics to tropical cyclones in general. Keim et al. (2007) determined return periods for storms of varying intensities at 45

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United States coastal locations. Elsner et al. (2006) determined the return periods along the

United States coastline for a storm with an intensity equivalent to Hurricane Katrina.

Climate teleconnections present another area of investigation. Teleconnections vary on

time scales from approximately 18 months for El Nino-Southern Oscillation (ENSO) to several

decades in the case of the Atlantic Multidecadal Oscillation (AMO). Climate oscillates in a

somewhat regular manner; once a new phase begins, it is likely that the new phase will remain in

place for approximately the expected phase length. These phases are not concrete, and

fluctuations between phases may occur at intermittent time scales. However, these

teleconnections provide a good context for determining tropical cyclone intensity. In this chapter,

surge frequencies within each teleconnection phase will be mapped, and the result will provide

spatial context for surge events.

Gray (1984) proposed a link between ENSO and tropical cyclone activity in the Atlantic

basin. In El Nino years, enhanced convection over the normally cold waters off the coast of Peru

increases upper level wind shear across the tropical Atlantic. This shear diminishes tropical

cyclone intensity, and as a result, El Nino years tend to see less intense hurricane seasons in the

ACUS. La Nina has the opposite effect, as the super-normal conditions promote very cold waters

off the Peruvian coast. The associated lack of convection reduces wind shear and cyclonic

development is enhanced. The AMO is another controlling factor on cyclonic development in the

Atlantic Basin. Saunders and Harris (1997) connected the active 1995 season to anomalously

warm SST in the Atlantic. Landsea et al. (1999) determined a statistically significant link

between north Atlantic SSTs and frequency and intensity of tropical cyclones. These

teleconnections can also work in concert with each other. Klotzbach (2011) determined that in

the 10 strongest La Nina years with a positive AMO, 29 tropical cyclones tracked through the

Caribbean, while in the 10 strongest El Nino/negative AMO years, only 2 tropical cyclones were observed in the Caribbean.

These links between tropical cyclone activity and teleconnections is well-accepted in the scientific community. These studies provide no insight into associated hazards, though. An investigation into potential correlations between oscillatory phases and observed storm surge would provide more depth to the study of tropical cyclones, and increase the robustness of the aforementioned connections. Thus, in addition to determining spatial variability of storm surge, links between surge events and these teleconnections will also be examined. Surge magnitudes and frequencies will be statistically tested to determine what, if any, control teleconnections exert on surge characteristics. Through mapping surge events and statistical tests, a greater understanding of processes that control storm surge can be gleaned.

3.2 Spatial Distribution of Surge Events

3.2.1 Mapping Surge Events

Each of the 72 surge events produced a peak surge at one specific location. This location was translated into its associated latitude and longitude coordinates. This allowed the surge events to be plotted, and an analysis of spatial distribution to be conducted. In addition to mapping all surge events, surge events are also plotted based on the phase of the AMO and SOI. This data file was loaded into ESRI's ArcGIS software, and a variety of output maps were created. The data file produced and uploaded into ArcGIS lays the groundwork for future storm surge analyses. Other teleconnections or indices (for example, the North Atlantic Oscillation) may be added for analysis in future studies.

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3.2.1.a All Surges

The output map for all surge events is found in Figure 3.1. Surge events are represented by red dots on the map. The most immediate observation is the contrast between the northern ACUS and southern ACUS. Only 17 of the 72 surges in the dataset (23.6%) occur north of the North Carolina/Virginia border. Moving the arbitrary cutoff north by about 30 miles to include the Newport News area of southern Virginia as part of the southern ACUS, this number drops to 12 of 72, or 16.7%. It is also interesting to note that most of the northern ACUS observations occur at or in the vicinity of the large, historic cities of New York, NY and Providence, RI. This could be an observation bias; especially in the early part of the dataset, smaller events may have been missed had they occurred outside of these areas. No matter the reason, the data shows an increased surge risk in these larger population centers.

Within the more active southern region, surge distribution is not evenly distributed. Southern North Carolina (around Wilmington) and south Florida (Miami metropolitan area) seem to be the two focal points of surge activity, with both regions seeing numerous events concentrated in a small area. Less active areas include north Florida, Georgia and the area surrounding the North Carolina-South Carolina border. This was an expected result, as the convex nature of this stretch of coastline precludes tropical cyclones from making landfall in these regions. However, it should be noted that the areas in the less-active regions are not immune to surge events. Though they are statistically less likely to see a surge than the more active regions, the potential exists for a surge event in these locations.
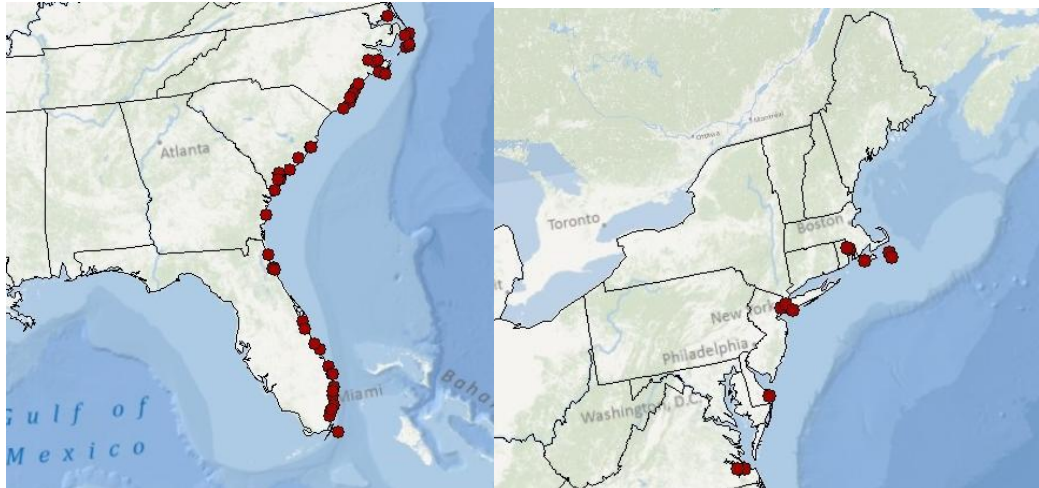
(a)   (b)

Figure 3.1: Spatial distribution of storm surge events, 1898-2011, for (a) the southern half of the ACUS and (b) the northern half of the ACUS.

3.2.1.b Surge Events Based on AMO Phase

Surge events were then mapped based on AMO phase. The resultant maps are found in Figure 3.2a (warm phase) and Figure 3.2b. (cold phase). Forty of the 72 events in the dataset (55.5%) occurred during AMO warm years, while 32 (44.4%) occurred in cold years. From 1898-2011, 52 years were classified as AMO warm, while 62 were classified as AMO. On average, AMO warm years feature 0.77 surge events/year, and AMO cold years feature 0.52 surge events/year. Table 3.1 contains a list of all surge events, separated by AMO phase. This follows the theory that AMO warm years produce more storms than cold years. In anomalously warm years, increased evaporation causes an increase in atmospheric water vapor content. Additionally, warmer SST are generally associated with lower than average sea level pressure readings. This diminishes trade winds, which in turn diminishes vertical wind shear, enhancing cyclogenesis (Landsea et al. 1999). Geographically, it is difficult to discern if certain areas are favored in one phase or another, as the data points for the cold years are more sparse. It should

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be noted that this analysis is based strictly on frequency of events; a statistical analysis of surge heights and AMO phase appears later in this chapter.

Table 3.1: List of surge events, separated by AMO phase, 1898-2011.

AMO Warm		AMO Cold	
Year	Surge (m)	Year	Surge (m)
1898	5.49	1903	1.52
1899	2.44	1903	2.07
1926	3.75	1906	2.13
1926	2.26	1911	1.8
1928	3.41	1914	1.52
1928	3.35	1918	2.47
1933	2.53	1947	2.29
1933	2.99	1947	3.47
1934	1.22	1950	1.52
1935	2.13	1959	1.22
1936	2.83	1959	3.05
1938	6.49	1964	1.83
1940	3.44	1964	3.66
1944	3.2	1965	1.52
1944	3.23	1967	1.71
1945	3.66	1968	1.52
1949	2.1	1971	1.22
1953	1.83	1971	1.22
1954	2.99	1976	1.37
1954	4.54	1979	3.78
1955	1.65	1984	1.68
1955	2.74	1985	2.1
1955	3.23	1986	1.22
1956	1.34	1986	6.1
1958	1.31	1991	2.13
1960	2.19	1992	5.15
1998	1.53	1992	1.65
1999	2.41	1993	2.99
1999	2.1	1996	1.74
2002	1.68	1996	2.74
2003	3.28	1996	1.22
2004	1.83	1996	3.66
2004	2.29		
2004	1.37		

Table 3.1 continued

2004	2.44
2004	1.83
2005	1.52
2008	1.52
2010	1.31
2011	2.16
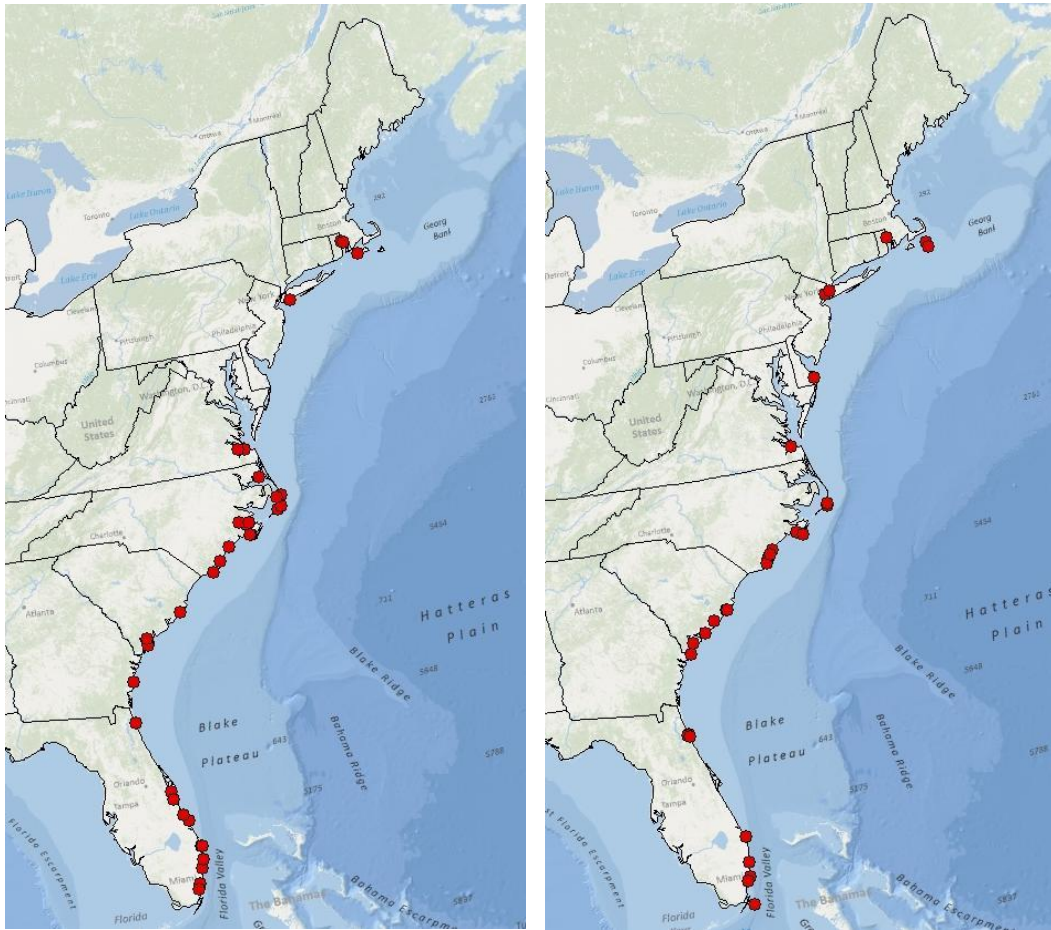
(a)   (b)

Figure 3.2: Distribution of surge events occurring during AMO warm years (a), and AMO cold years (b), 1898-2011.

3.2.1.c Surge Events Based on SOI Phase

Surge events were also mapped based on SOI phase – positive (La Nina) or negative (El Nino) (Figure 3.3). SOI data is available until 2009 from the University of East Anglia; therefore, this analysis is truncated at 2009. In contrast to the AMO distributions, the split of La Nina and El Nino events was roughly the same. Thirty-six surge events occurred in La Nina conditions, while thirty-four occurred in El Nino years. The SOI index indicated La Nina conditions 56 times and El Nino conditions 56 times. Thus, the vulnerability to surge is roughly the same regardless of phase (0.64 storms/year and 0.61 storms/year, respectively.) Table 3.2 lists all surge events separated by ENSO phase. This is in contrast to the widely held belief that La Nina years feature enhanced storm activity while El Nino years feature diminished storm activity (Bove et al. 1998). However, this analysis is strictly based on the number of surge events; later in this chapter, an analysis of surge magnitude versus SOI will be conducted.

3.3 Temporal Trends in Surge Frequency and Magnitude

3.3.1 Annual Frequency Series

Graphical representations of storm surge activity provide a simple yet effective means to analyze trends through time. Thus, an annual frequency series of storm surges was created. An annual frequency series plots the number of surge producing events versus time, providing insight into how surge trends have changed through time. Surge events were divided into two categories for this analysis: major - surge height > 2.75 m (9 ft), and minor - surge height < 2.75 m (9 ft.)

Table 3.2: List of surge events, separated by ENSO phase.

La Nina Years		El Nino Years	
Year	Surge (m)	Year	Surge (m)
1898	5.49	1899	2.44
1903	1.52	1911	1.8
1903	2.07	1914	1.52
1906	2.13	1918	2.47
1928	3.41	1926	3.75
1928	3.35	1926	2.26
1933	2.53	1934	1.22
1933	2.99	1936	2.83
1935	2.13	1940	3.44
1938	6.49	1944	3.2
1945	3.66	1944	3.23
1947	2.29	1949	2.1
1947	3.47	1953	1.83
1950	1.52	1958	1.31
1954	2.99	1959	1.22
1954	4.54	1959	3.05
1955	1.65	1965	1.52
1955	2.74	1968	1.52
1955	3.23	1976	1.37
1956	1.34	1979	3.78
1960	2.19	1984	1.68
1964	1.83	1985	2.1
1964	3.66	1986	1.22
1967	1.71	1991	2.13
1971	1.22	1992	5.15
1971	1.22	1992	1.65
1989	6.1	1993	2.99
1996	1.74	2002	1.68
1996	2.74	2003	3.28
1996	1.22	2004	1.83
1996	3.66	2004	2.29
1998	1.83	2004	1.37
1999	2.41	2004	2.44
1999	2.1	2004	1.83
2005	1.52		
2008	1.52		
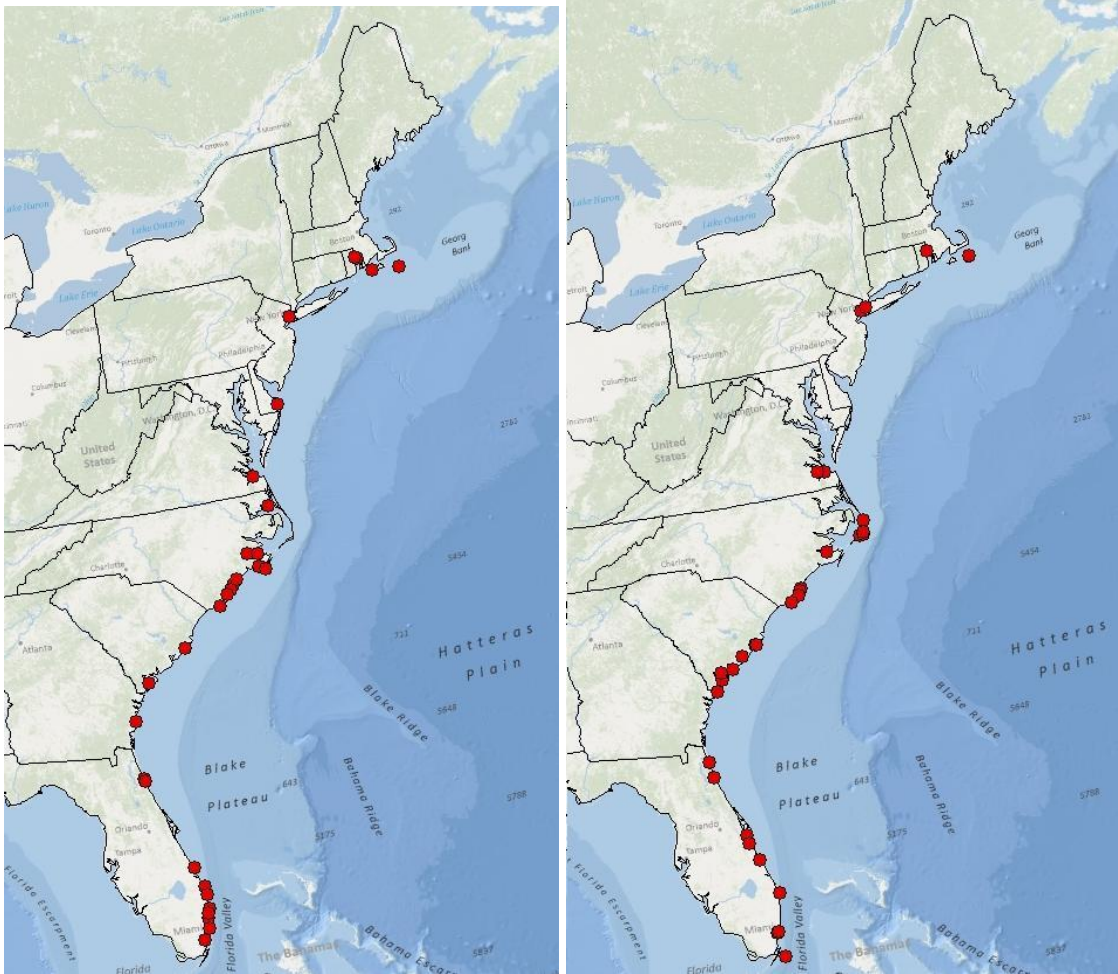
(a)   **(b)**

Figure 3.3: Distribution of surge events during La Nina years (a), and El Nino years (b), 1898-2011.

The time series (Figure 3.4) has a few interesting features. Most notably, there is a distinct dearth of events prior to 1926. It is possible that the first few decades of the 20th century were a historically inactive period for tropical cyclone development. However, this is more likely a result of a poor observational network at that time (Landsea et al. 1999). In 1900, the population of the United States was slightly more than 76,000,000. By 1940, this figure had nearly doubled to over 132,000,000 (United States Census Bureau). An increase in population might not have affected the count of landfalling tropical cyclones, as tropical cyclones tend to

affect a large area and even in the pre-radar time period, the US Weather Bureau tracked nearly every storm that threatened landfall in the United States. However, a doubling of population likely has significant impacts on surge records. Every landfalling storm produces surge, but not every surge event occurs in a populated area. A less populated region and thus a larger percentage of uninhabited area naturally leads to a number of surge events going unrecorded. This likely explains most of the surge inactivity at the start of this dataset.

Another potential controlling factor of not only the initial lack of storms but the secondary deficit from 1970-1990 is probably related to the natural fluctuation of sea surface temperatures (SST) (Landsea et al. 1999). These fluctuations, termed the Atlantic Multidecadal Oscillation (AMO), were first identified by Schlesinger and Ramankutty in 1994, and are clearly evident in the record. Several studies (Vitart and Anderson, 2001); (Zhang and Delworth, 2006) have identified links between AMO phase and Atlantic hurricane activity, with warm phases generally seeing increased hurricane activity and vice versa.

AMO is calculated through the Columbia University's International Research Institute database. SST anomalies (2.5^o resolution) were calculated for the north Atlantic basin (0-90 W, 0-70 N), detrended over temperature and averaged over the x-y plane for 1890-2011. Anomalies are displayed in Figure 3.4. Comparing SST anomalies to the annual frequency series reveals some other links. Of the 23 major surges in the dataset, 17 of these events (73.9%) occurred during years with a positive (warm) SST anomaly. The previously mentioned lack of storms from 1970-1990 also lines up with a mostly negatively (cold) anomalous period. Later sections in this analysis will provide statistical insight into potential correlations between the AMO and surge activity.
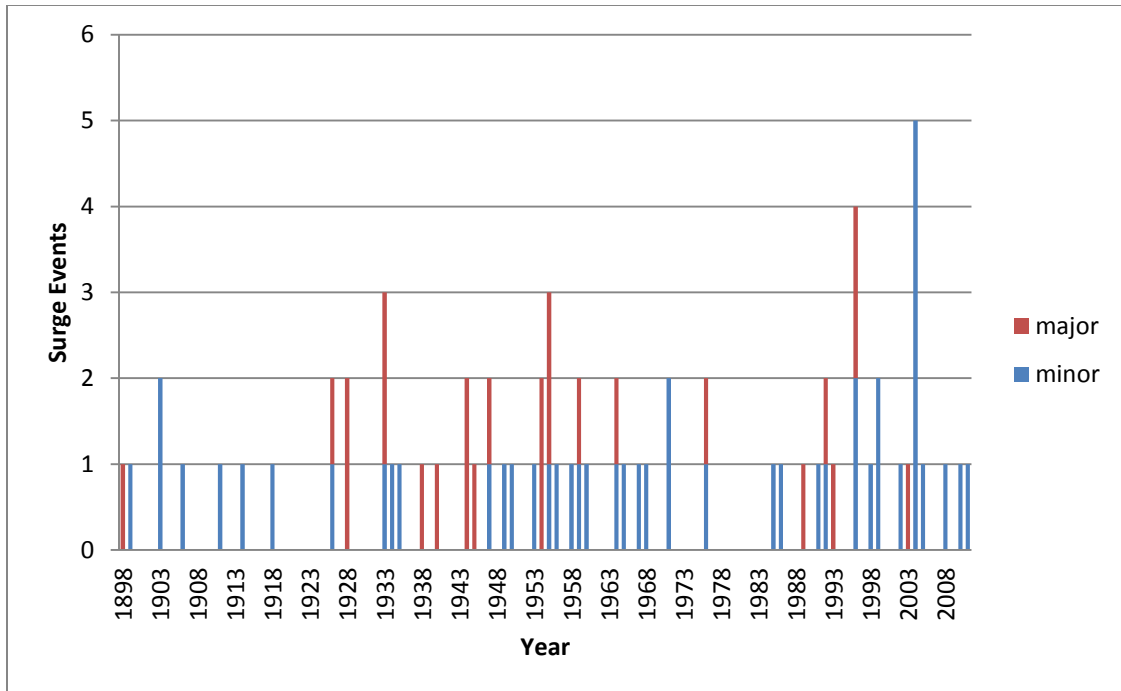
Figure 3.4: Annual frequency series of surge events along the Atlantic coast of the United States, 1898-2011. Minor events (< 2.75 m) are represented by blue bars; major events (>2.75 m) are represented by red bars.
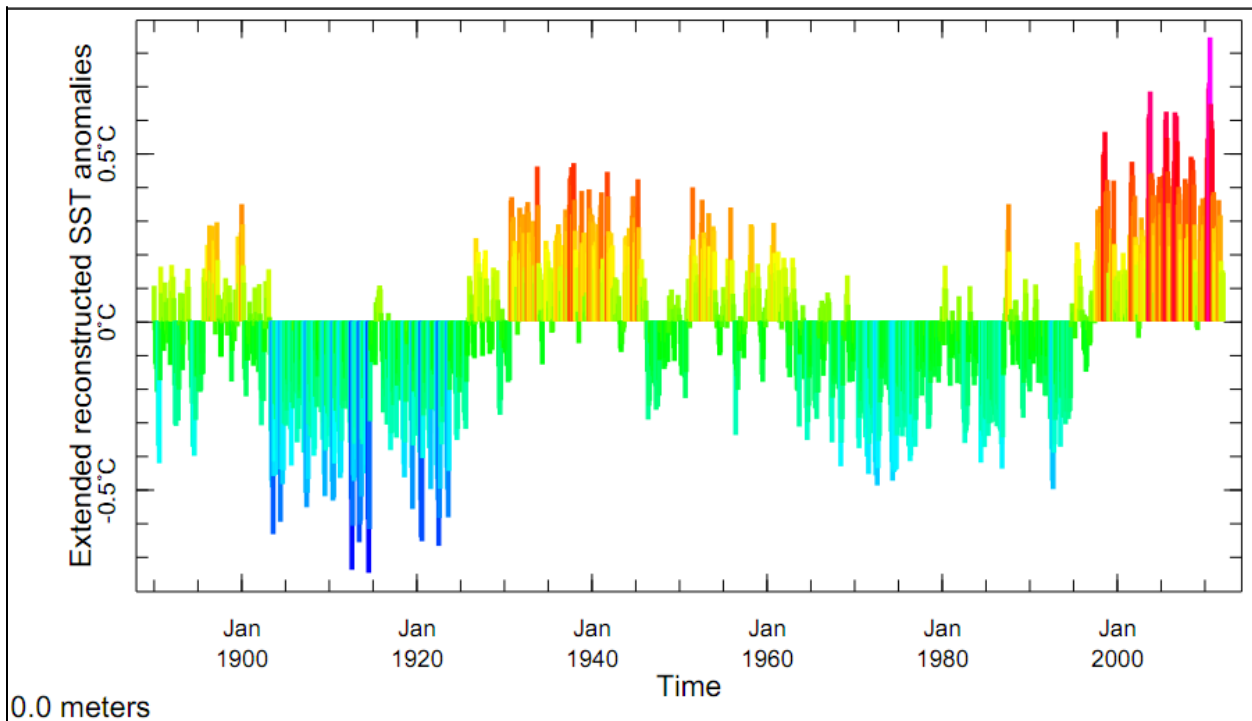
Figure 3.5: SST anomalies for the north Atlantic basin (0-90 N, 0-70W), 1898-2011. (Columbia International Research Institute)

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3.3.2 Annual Maximum Series

To determine how maximum surge heights have changed through time, an annual maximum series was created. The largest surge event for each year with at least one surge event was determined and plotted against time. (Figure 3.6)

Trends in this graph mostly follow those seen in the frequency series. Every year that is represented in the frequency series is also represented here. Rather than analyzing on the count of surge events, the magnitudes provide additional insight into surge patterns. The largest values in the maximum series occurred in 1938, 1989, 1992 and 1954, respectively. Although these years saw anomalously high surge events, they were not all overly active years in terms of basin-wide surge events. The years 1938 and 1989 did not see any other surge-generating events along the ACUS, and 1992 only featured one other, minor event. However, 1954 was a more active season, with three surge events, two of which were major.

Examining the graphs from the reverse perspective, the four most active years in terms of the frequency series were 1933, 1954, 1996 and 2004. Annual maximum surge heights for each of these years were 3 m, 4.6 m, 3.7 m and 2.4 m, respectively. In terms of distribution between major and minor surges, 1933, 1954 and 1996 all saw at least half of the surge events classified as major, while every 2004 event was minor. This is an interesting observation, as 2004 was also the year with the most surge events in the dataset (five). It is possible that the 2004 information is anomalous, as the maximum surge heights in the other high frequency years all rank in the top third of surges in the dataset.
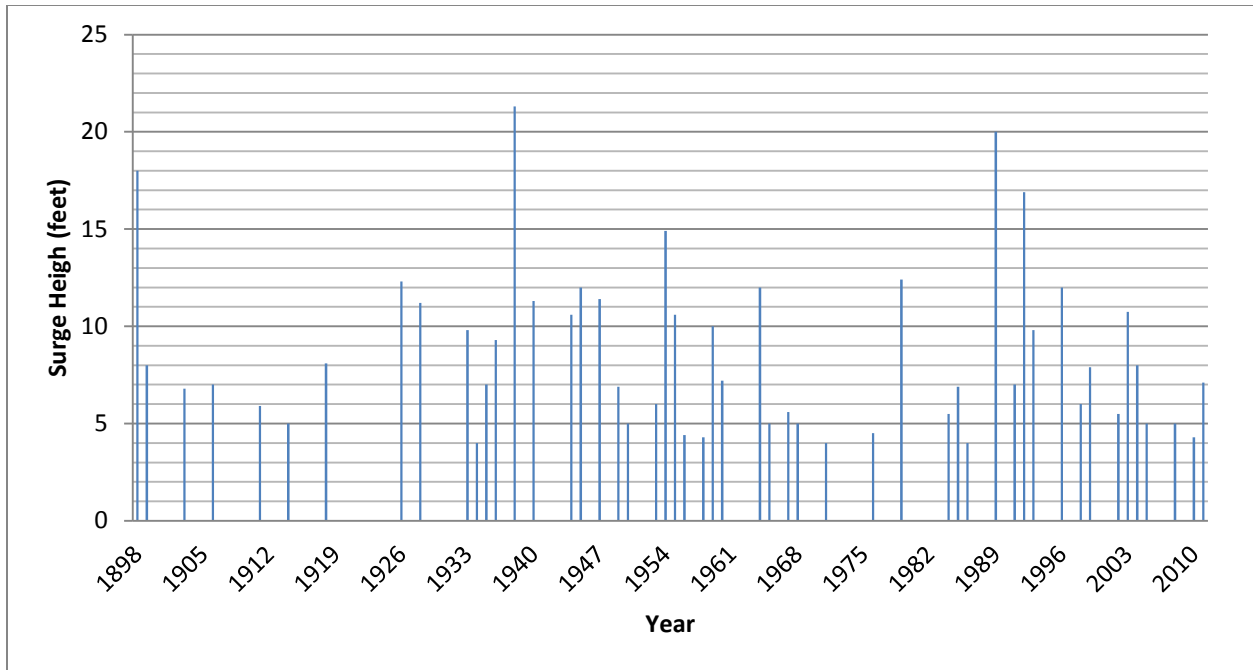
Figure 3.6: Annual maximum series of surge events for the Atlantic Coast of the United States, 1898-2011.

3.4 Statistical Perspectives on Storm Surge Activity

3.4.1 Testing Data for Normality

Statistical analysis of storm surge heights and climatic teleconnections provides insight into an under-researched area. Although links between tropical cyclones and teleconnections have been generally accepted, surge heights have not been tested versus these variables. This section aims to fill that void for the ACUS by conducting correlation tests on surge heights and teleconnections. To determine the proper test to use, normality of the dataset must be assessed.

Normality was determined through the Shapiro-Wilk normality test. This test returns two output parameters: a W-score and a p-score. As the W-score approaches 1, normality increases. However, if the p-score does not exceed 0.05, we must fail to reject the null hypothesis

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regardless of the W-score (Chen 1971). Here, the null hypothesis states that the data are not normally distributed.

The Shapiro-Wilk test results are found in Table 3.3. The W-score is quite high at 0.8614. However, the p-score is exceptionally low, falling very far below the 0.05 threshold. As a result, the dataset is not normally distributed. Because of this non-normal distribution, the following sections will employ a Spearman correlation test to determine correlations between surge heights and teleconnections.

Table 3.3: Results of the Shaprio-Wilk normality test. As W-score approaches 1, normality increases; however, if p-value does not exceed 0.05, this score is irrelevant and we fail to reject the null hypothesis.

	W-score	p-score
Shapiro-Wilk test	0.8614	<0.00001

3.4.2 Atlantic Multidecadal Oscillation (AMO)

The AMO Index measures fluctuations in sea surface temperatures (SST) in the north Atlantic basin. Several AMO indices are available from various sources; for the purpose of this study, an AMO chart was created using SST anomalies (see Section 3.3.1 for parameters used in creation of chart.) The resultant chart shows a clear shift between warm and cold phases, with each phase persisting mostly uninterrupted for several decades. Correlations between hurricane activity and AMO phase have been proven by several studies, but no analysis into surge heights and AMO phase has been conducted until this point.

SST anomalies were calculated in Microsoft Excel using the output data provided in the creation of the chart. AMO values were calculated for each surge event at a yearly and monthly

scale. The yearly scale is an average of all SST anomalies for the year in question, and the

monthly values are for the month in which the surge event occurred.

3.4.2.a Results of AMO Correlation

Yearly SST anomalies produced an r_s score of 0.1481, p-value of 0.2144. Because this p-

score is not less than 0.05, this value is not statistically significant. At the monthly level,

correlation testing revealed an r_s-score of 0.1551, p-value of 0.1933. These values are also

statistically insignificant. Results of the Spearman test can be found in Table 3.4.

Table 3.4: Results of the Spearman correlation test between surge heights and AMO for the year as well as specific month in which the surge event occurred. Red cells indicate values that are not statistically significant at the p=0.05 level.

Variable	r_s-score	Probability value
AMO-Yearly	0.1481	0.2144
AMO-Monthly	0.1551	0.1933

In addition to testing surge heights versus their AMO phase, a test of surge frequency in

all AMO warm years versus all AMO cold years was performed using the Wilcoxon signed-rank

test. This test is used to compare two sets of non-parametric data (Forreste and Ury 1969).

Results of the Wilcoxon test show results significant at $\alpha \leq 0.10$ (p = 0.859.) Hence, we can say

with 90% confidence that there is a significant difference in the number of surge events in AMO

warm years versus AMO cold years. This backs up the graphical output from Figure 3.2.

Results of these analyses provide some insight into surge activity and SST. Pearson

correlation tests did not indicate any statistical significance between surge magnitude and AMO

phase. Although this is counter to the literature, it is possible that the small sample size resulted

in these insignificant results. A Wilcoxon signed-rank test did find significance at the 90%

confidence level between the number of surge events per year and AMO phase. This result

indicates that AMO warm years tend to produce a higher number of surge events, which validates the empirical results discussed in Section 3.2.1.b.

3.4.3 Southern Oscillation Index (SOI)

The SOI is the atmospheric component of El Nino-Southern Oscillation (ENSO). It is calculated as the difference in air pressure anomalies between the French Polynesian island of Tahiti and the Australian city of Darwin (Ropelowski and Jones 1987). Links between ENSO phase and hurricane activity are well-established, with El Nino years generally associated with suppressed tropical activity in the Atlantic basin, and vice versa (Gray 1984). Convection centers in the equatorial Pacific shift east in El Nino years, causing an increase in westerly winds and thus, an increase in vertical wind shear in the main Atlantic development region (Goldenberg and Shapiro 1996). This increase in vertical wind shear discourages tropical cyclone development in the Atlantic. In ENSO-neutral and La Nina years, convection is muted, and the lower wind shear encourages tropical cyclone development. Gray (1984) demonstrated that during non-ENSO years, the frequency of landfalling hurricanes in the United States increases threefold. The reasons for choosing the SOI over more common SST measurements of ENSO such as Nino 3.4 are twofold: (1) SOI records available from the University of East Anglia extend back to 1866, while most SST calculations extend only to 1951, and (2) SOI is the atmospheric component of ENSO; hurricanes are atmospheric as well as surface phenomena and thus it is valuable to include an atmospheric indicator.

SOI values were obtained from the University of East Anglia for most of the period of record (1898-2009, where the East Anglia dataset ends). Positive values are associated with La Nina conditions, and negative values with El Nino. In accordance with Needham (2010) and

Elsner et al. (2008), the analysis began with a correlation between surge heights and the August-October (A-S-O) averaged SOI. This value provides the phase of the SOI during the height of hurricane season. Additionally, three-month averages were calculated for the six months leading up to hurricane season. The indices are: July-August-September (J-A-S), June-July-August (J-J-A), May-June-July (M-J-J), April-May-June (A-M-J), March-April-May (M-A-M), and February-March-April (F-M-A). These indices were calculated because ENSO events can still exhibit influence on climate for a few months after the demise of the event (Kozlenko et al. 2009). Thus, knowledge of ENSO phase in the months leading up to a surge event may provide better correlation between surge height and ENSO phase.

3.4.3.a Results of SOI Correlation

The three peak months of hurricane season (A-S-O) produced an r_s-score of 0.0412, with a p-value of 0.7312 (Table 3.5). As with the AMO correlation, none of the calculated values are statistically significant. In fact, these values generally produced p-values that are very high, indicating a distinct lack of statistical significance. R_s scores also fluctuated between negative and positive values while remaining around zero, further indicating a lack of correlation.

Table 3.5: Results of the Spearman correlation test between surge heights and SOI index for the seven calculated indices. Red cells indicate values that are not statistically significant at the p=0.05 level.

Variable	r_s-score	Probability value
SOI - ASO	0.0412	0.7312
SOI - JAS	0.1294	0.2848
SOI - JJA	0.0135	0.9114
SOI - MJJ	-0.1076	0.3683
SOI - AMJ	-0.0533	0.6607
SOI - MAM	-0.0189	0.8761
SOI - FMA	0.0073	0.9514

Next, a Wilcoxon signed-rank test was utilized again to determine if a connection between ENSO phase and surge frequencies exists. Results show an insignificant association ($p = 0.2178$.) This is an expected result, as Figure 3.3 indicates roughly the same number of surge events in El Nino and La Nina years.

These results are extremely interesting, and tend to agree with the spatial display of data in Section 3.2. Dividing surge events into La Nina and El Nino years yielded a similar number of events in each year. Based on these correlation tests, it is assumed that not only does frequency of surge events not vary with ENSO phase, but the magnitude of these events is also not influenced by this phenomenon. This is counter to the generally agreed upon theory that tropical cyclones in the Atlantic tend to increase in frequency and magnitude in La Nina years. Further trend testing in other regions of the world may help corroborate or disprove these results.

3.5 Summary and Discussion

The perspectives on storm surge presented in this chapter provide insight into a variety of factors that control surge as well as regions that are vulnerable to surge events. Mapping all surge events showed a considerable difference in events between the southern half of the study area and the northern half. This was expected, as the southern half of the region is located near warmer waters and also closer to the development region of tropical cyclones. Distribution of surge events was not homogenous amongst the more active southern half, with south Florida and southern North Carolina serving as the two most active regions. This was also expected, as the curvature of the coastline and the exposure of these areas to the ocean encourages landfall in these regions. Results generally follow the spatial distributions calculated by Keim et al. (2007).

When surge events are separated based on oscillation phase, several things become apparent. First, the majority of surge events occurred during the AMO warm phase. This phase is

characterized by anomalously warm SST in the Atlantic, so this result was expected. When events are divided based on SOI index, the roughly the same amount of surge events occurred in both La Nina and El Nino years. This was counter to expectations, as El Nino events generally produce less or weaker hurricanes than during La Nina events. It is important to note that these output maps do not take surge magnitude into account, only frequency.

Next, an investigation into temporal surge distribution was undertaken. An annual frequency series and annual maximum series were produced. These graphs provide a perspective to which seasons were most active, and which seasons produced the largest surge events. These results were visually compared to calculated SST anomalies, representative of the AMO. Not surprisingly, AMO cold years tended to see a decline in both surge events and heights, while warm years tended to ramp up both of these variables.

Finally, several parameters were statistically tested to determine correlation with surge height through a Spearman test. Tests of SST anomalies on both yearly and monthly scales revealed no significance for either test. The SOI index was tested through seven indices – the three months of hurricane season and all three-month averages dating back for six months. All seven indices proved insignificant. A Wilcoxon signed-rank test was performed on both AMO and SOI versus surge frequencies to determine statistically whether teleconnection phase influences frequencies. The AMO test proved to be significant at the 90% confidence level, while the SOI test was not significant.

The results of these analyses have much utility. Spatially speaking, there is clearly an uneven distribution of risk along the Atlantic Coast. Frequencies of occurence follow what would be expected, with southern regions more vulnerable (although this risk is not evenly

distributed.) Chapter 4 will provide an in-depth analysis of regional vulnerability to storm surge events.

The AMO analysis mostly follows the scientific literature. A simple count of surge events based on phase revealed a majority of surge events occurring in AMO warm years. This was verified by the Wilcoxon test. It is safe to conclude that, based on these data, AMO phase is a controlling factor of surge frequencies along the ACUS. Warm years tend to have an increase in surge events, while activity is diminished in cold years.

The results differ from the literature when magnitude is analyzed. No statistical significance was discovered between surge magnitude and AMO phase of both the year and month that the event occurred in. There are several possible explanations for these results. The small sample size is one possible explanation for these results; with more data, a signal may emerge. Speculatively, it is possible that the AMO is associated with the number of storms but not the intensity, which is influenced by many other variables such as angle of approach, coastline shape, etc. (see Section 1.2.3 for a discussion of these factors.) A link between storm counts and AMO phase has been documented (Nigam and Guan 2010; Delworth and Mann 2000). However, links between intensity and AMO phase are not as clearly defined. These results suggest that such a link does not exist.

The SOI analysis also provided insignificant correlation to surge heights. These results do not agree with the consensus that La Nina years tend to experience an increase in storm intensity. This previous research does not investigate storm surge, though. These results show that there is no significant correlation between SOI index and surge heights at any of the seven intervals tested.

The sample size caveat applies to the SOI analysis as well as the AMO analysis. However, the results are consistent across all analyses performed in this chapter for SOI. The insignificance in surge frequency is especially noteworthy, as many studies (e.g. Elsner et al. 2001) have found a significant decrease in Atlantic tropical cyclones in El Nino years. One possible explanation is that ENSO phase controls storm counts, but not storm intensity and thus, surge heights. Another possibility is that ENSO phase alone does not determine tropical cyclone frequency or intensity. It is possible that other teleconnections such as the AMO and North Atlantic Oscillation, which controls Bermuda High strength and thus storm tracks, exert more influence on Atlantic surge patterns than ENSO. A study to determine which teleconnection has more control of surge heights may provide insight into these relationships. Finally, it is possible that the inclusion of only tropical storms producing a surge of greater than 1.22 m resulted in the omission of a number of storms that made landfall in La Nina years, but did not produce a large enough surge event to be included in the database. If the full record of Atlantic tropical storms is analyzed, significant results may emerge. The fact that using a non-complete storm record removes significance may indicate that this is the case, and ENSO phase exerts more influence on minimal tropical cyclones than larger storms.

CHAPTER 4: DETERMINING RETURN PERIODS AT A BASIN-WIDE AND REGIONAL SCALE

4.1 Introduction

The United States ranks as the third most populated country in the world, trailing only the immense populations of China and India. Although the growth rate of the country as a whole is expected to slow in the coming decades (Day 1993) this trend will not be homogenous throughout the nation. Population centers have undergone many shifts throughout the nation's history, but coastal areas have always been hot spots of population and development. The present is no exception. From 1970-2000, nearly every coastal county on the Eastern Seaboard saw population growth, and in many cases the growth was substantial (University of South Carolina 2012).

The trend of increasing coastal population seems to be entrenched in the country's demographic profile, in spite of the ever-present threat of tropical cyclones. Interestingly, some of the fastest growing areas since 1970 are in Florida, a state perhaps most famous for its vulnerability to tropical cyclones. Although the state is a historically vulnerable region, the past four decades have been relatively quiet in Florida (Keim et al. 2007). This lull in activity likely led to a building boom in coastal regions. It is foolish, however, to assume that this dearth of landfalling tropical cyclones means the Florida coast is a sustainable place to develop. In this chapter, storm surge quantiles will be generated to determine return periods for the entire Atlantic Coast of the United States (ACUS) as well as distinct regions. Through these estimations, vulnerability may be assessed, and a historical context of surge events is created. This information provides a clearer picture of the potential magnitude of surge events for a particular area and may be used as a guide to help govern coastal development.

4.2 Return Periods on a Basin-Wide Scale

4.2.1 Introduction

The ACUS stretches over 2,000 miles from the US/Canada border in Maine to, for purposes of this study, the northernmost extent of the Florida Keys in south Florida. This extensive coastline taken in concert with the very active tropical cyclone development zone in the Atlantic Ocean and Caribbean Sea makes the ACUS one of the most vulnerable stretches of coast in the world with respect to tropical cyclones. Past research has sought to understand the return periods of tropical cyclones along this stretch of coast. Simpson and Lawrence (1971) provided insight into various tropical cyclone-related variables along 50-mile stretches of the US coast. This analysis provided risk of being impacted by a landfalling storm based on storm intensity (any storm, hurricane, "great" or major hurricane,) and provided a percent chance of experiencing an event in a given year for each segment. This analysis was groundbreaking at the time; however, improvements in the length of record and historical data may render this dataset unreliable.

A more modern take on return periods and distribution of intensity in tropical cyclones was published by Keim et al. (2007). Here, the authors use National Hurricane Center (NHC) 6-hourly data for every storm from 1901-2005 and 45 coastal point locations, rather than stretches of coast as in Simpson and Lawrence. Through these data, the authors provided a spatial distribution of landfalls, divided into the same categories in Simpson and Lawrence. The result is an updated version of the 1971 study, focused on points rather than segments and with a more complete dataset.

These studies, among others, provide insight into how vulnerability to a landfalling tropical cyclone vary spatially (and in Keim et al. 2007, temporally). These studies provide valuable information to the climatological community; however, vulnerabilities to individual hazards associated with these tropical cyclones are not discussed. This lack of information led to the creation of SURGEDAT and, in the analysis presented below, storm surge return periods and quantile estimations for the ACUS.

4.2.2 Methods

4.2.2.a Quantile Estimation Methods

To determine the best estimates of surge heights associated with specific return periods, three quantile estimation methods were employed. It should be noted that no one method is a perfect representation of the actual data, and different methods are more suitable to different types of analyses. Methods were partly chosen based on Needham (2010), which employed regression analyses as well as distribution fitting methods.

Two regression analyses were employed. The Huff-Angel method (Huff and Angel 1992) utilizes a scatter plot of points, with both the x-and-y-axes scaled logarithmically. A best-fit trend line is applied to the data points, and the resultant equation of the line provides expected surge heights for each return period. A similar method is described by Faiers et al. (1997), the so-called Southern Regional Climate Center (SRCC) method. This method is similar to the Huff-Angel; whereas Huff-Angel utilizes a log-log scale, SRCC estimates are produced through a log-linear graph, with the x-axis scaled logarithmically.

Needham (2010) employed two distribution methods – the beta-P and Gumbel methods. Both methods are fairly commonplace in analysis of physical data. However, these methods

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require a full partial duration series of events. Because of an insufficient number of events (averaging less than one per year), these methods do not apply to this dataset. Instead, the Pareto method was employed. This technique does not require a full partial duration series, and thus is applicable in this analysis. Once quantiles from each method were obtained, the Kolmogorov-Smirnoff (KS) association test revealed the method that best represents the expected distribution of surge magnitudes.

4.2.2.b Producing Quantile Estimates

Quantile estimates were calculated for 2-year, 5-year, 10-year, 20-year, 25-year, 50-year and 100-year return periods. Raw surge height data from SURGEDAT were entered in a spreadsheet. This list of storms was fitted to the Pareto distribution through two steps. First, surge heights were entered into the EasyFit distribution fitting software. This program provides three output parameters describing the distribution. These parameters allowed for the calculation of quantile estimates in the R computer programming language.

To determine the probability of receiving a surge event in a given year in the ACUS through the linear regression methods, probabilities of exceedence were calculated. These values were obtained through the formula "Exceedence Probability = Rank/(n+1)", where n = the number of years in the dataset (114), and rank of storms is determined by sorting surge heights from largest to smallest and assigning a rank to each (where 1 = largest surge event.) Low frequency, high magnitude events such as the Great New England Hurricane of 1936 (6.49 m storm surge, largest in the dataset) have a low annual exceedence probability (0.00877, or 0.87%), while high frequency, low magnitude events such as the glut of four-foot storm surges at the low end of the dataset have a higher exceedence probability (0.632, or 63.2%). Exceedence

probabilities are inversely related to return periods; that is, a low exceedence probability translates to a high return period. Return periods were calculated for each storm through the formula "Return Period = 1/Exceedence Probability." The 1936 New England storm has a return period of 115 years, or the "n+1" term in the exceedence probability equation, while a minimal surge event of 1.22 m has a return period of 1.58 years. Calculated return periods were plotted versus surge heights, and a trendline was created. This trendline was then used to determine surge heights associated with specific return periods.

4.2.3 Results

The three estimation methods produced a wide array of quantile estimations. Table 4.1 depicts quantile estimates for each of the three methods for selected recurrence intervals. Several things are apparent from this table. Most notably, the Huff-Angel regression overestimates the 100-year event, placing this value at 9.17 m. This value is nearly three meters greater than the other two methods, and exceeds the largest surge in the dataset by about 2.7 m. Another interesting feature is the overestimation of the medium-to-low frequency events by the Pareto distribution. This distribution produces a quantile estimate of 4.08 m for the 10-year event, a height that was attained only 5 storms in the entire dataset. At the 5-year level, the value of 3.29 m occurred only 14 times in the dataset. Each estimation method used results in different spread of quantile estimates. The results of these different methods are contained in Table 4.1. Regression plots for the SRCC and Huff-Angel methods can be found in Figures 4.1 and 4.2, respectively.

Figure 4.1: SRCC regression method to determine surge return periods for data from 1898-2011.

$y = 4.1178\ln(x) + 2.2392$
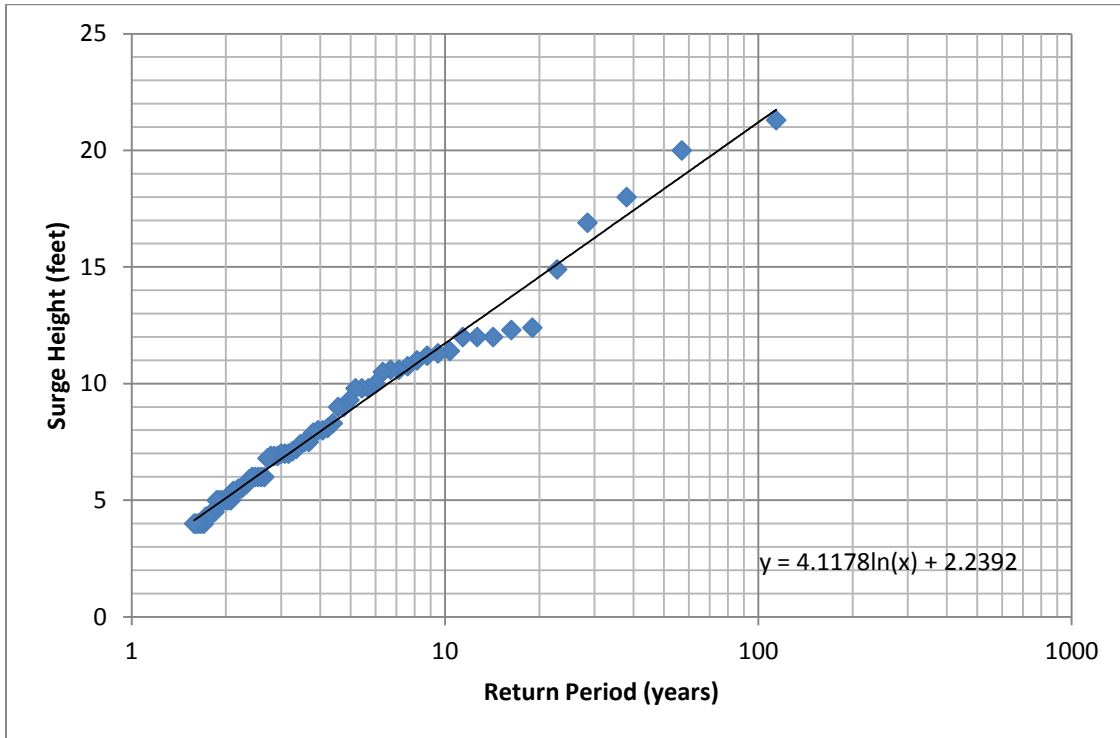
Figure 4.2: Huff-Angel regression method to determine surge return periods for data from 1898-2011.

$y = 3.9386x^{0.4417}$
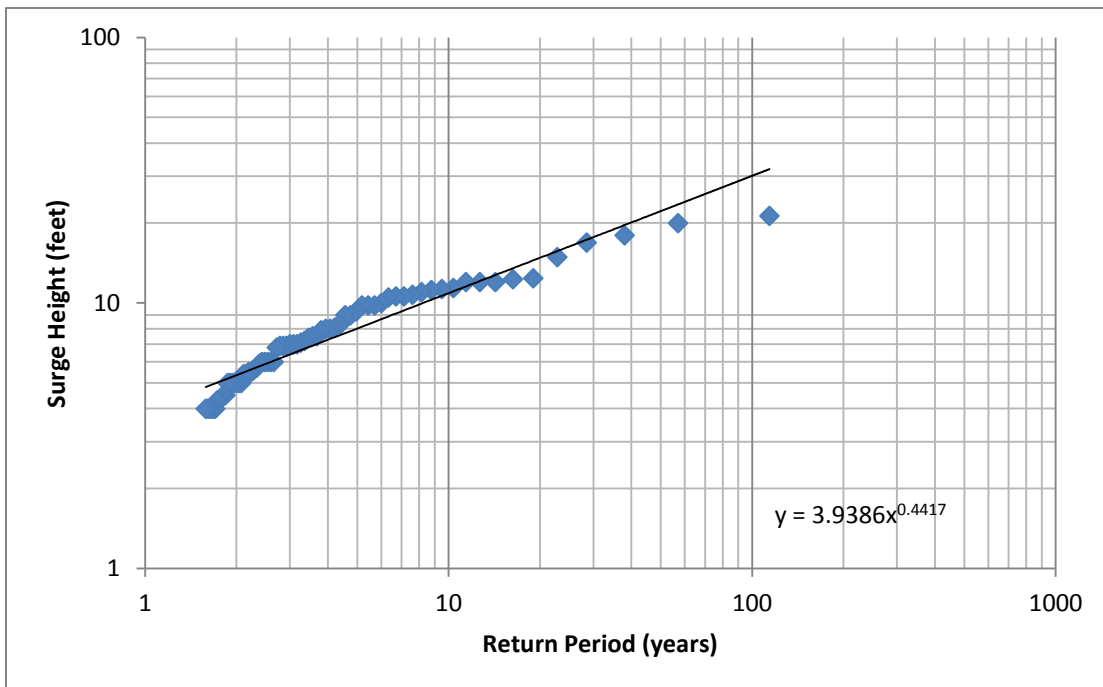
4.2.4 Determining Best Statistical Fit

Table 4.1 provides a visual representation of quantile estimates associated with each method. Although some obviously anomalous data exists, a visual analysis is not enough to determine the most accurate distribution. Thus, the Kolmogorov-Smirnoff (KS) test is used to provide statistical context to these results. The methodology presented below was amended from Keim and Faiers (2000.)

Accuracy of each estimation method is determined by comparing the number of "expected" storms for each return period to the number of observed storms above each threshold. The expected number of storms is a function of the length of the dataset. Here, n=114 years. Therefore, for a 100-year return period, one would expect (n/return period) storms to appear in the record. In this analysis, the expected number of 100-year storms is 1.14; that is, in strictly statistical terms, the record will likely have 1.14 storms with surge heights at or above the threshold of the 100-year quantile estimation. These thresholds, obtained through the quantile estimation processes detailed above and shown in Table 4.1, vary for each method. Thus, each method has a different number of actual surge events associated with each return-period. A comparison of the number of expected events and actual observed events for each method is presented in Table 4.2.

Table 4.1: Quantile estimates (in meters) for each of the three techniques employed in analysis.

Return Period	SRCC	Huff-Angel	Pareto
100-year	6.49	9.17	6.25
50-year	5.58	6.77	5.64
25-year	4.72	4.97	5.00
20-year	4.45	4.51	4.79
10-year	3.57	3.32	4.08
5-year	2.71	2.44	3.29

Table 4.1 continued

2-year	1.55	1.62	2.13

Table 4.2: Comparison of expected events for each return-period versus actual events for each technique. Actual events calculated as (years in dataset+1/return period).

Return Period	Expected Events	Actual Events (SRCC)	Actual Events (Huff-Angel)	Actual Events (Pareto)
100-year	1.14	1	0	2
50-year	2.28	2	0	3
25-year	4.56	4	4	4
20-year	5.7	5	5	4
10-year	11.4	12	14	5
5-year	22.8	25	29	14
2-year	57	54	54	38

The KS test was utilized to determine the best fit distribution for the surge events. The KS test provides an output statistic, known as the KS number. This number represents the goodness of fit between the expected events and observed events, with a smaller number corresponding to less error in the fit and thus a better distribution. The SRCC method produced the best fit, with a KS score of 0.02, followed by the Huff-Angel and Pareto distribution. Table 4.3 lists each method and associated KS score. Quantiles provided by the SRCC method, and thus the accepted quantiles for this analysis, are listed in Table 4.4

Table 4.3: KS test results for each technique. A lower score indicates a better fit.

	SRCC	Huff-Angel	Pareto
K-S Statistic	0.02	0.05	0.07

Table 4.4: Quantile estimates produced by the SRCC method, in meters. This method was determined to have the best fit, and thus the accepted values for this study.

Return Period	SRCC
100-year	6.49
50-year	5.58

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Table 4.4 continued

25-year	4.72
10-year	3.57
5-year	2.71
2-year	1.55

4.2.5 Determining Validity of Quantile Estimates

The quantile estimation methods undertaken in the previous section are based off the entire 114 year data set. As previously mentioned, however, the observational record for the first half of the data set may not be of the same quality as the latter half of the record. Thus, it is useful to use the SRCC method to determine quantile estimates for truncated versions of the data set. This will determine the reliability of the quantiles accepted in section 4.2.4.

Two truncated data sets were used in this analysis: all surge events from 1944-present, and from 1966-present. These dates were chosen because of technological advances that occurred in those years. The year 1944 featured the advent of aircraft reconnaissance missions into tropical cyclones east of $55^o\,W$ in the Atlantic Ocean (Landsea 2007). In 1966, the first geostationary satellite was implemented, ushering in the modern era of tropical cyclone tracking where no storms are unseen (Landsea 2007).

Results of the SRCC regression analysis for each of the three time series (1898-present, 1944-present and 1966-present) are found in Table 4.5. Quantile estimates vary little between the time periods, with some values for the same return period being exactly equal. To determine the statistical validity of these results, a Kruskal-Wallis one-way analysis of variance (KW) test was performed. The KW test compares variance across any number of data arrays (here, three arrays) and the resultant p-value determines whether the null hypothesis that the arrays are not

significantly different is rejected. A p-value greater than 0.05 results in a failure to reject the null

hypothesis (Kruskal and Wallis 1952). The results indicate strong similarity amongst the three

data sets ($p = 0.9825$; KW statistic $= 0.0353$.) This validates the SRCC method of quantile

estimation as an acceptable method, in spite of a potential observational bias.

Table 4.5: Quantile estimates (in meters) determined through the SRCC method for 1898-present (full data set), 1944-present (advent of aircraft reconnaissance) and 1966-present (advent of geostationary satellites.)

Return Period	1898-present	1944-present	1966-present
100-yr	6.49	6.37	6.53
50-yr	5.58	5.5	5.63
25-yr	4.72	4.73	4.73
20-yr	4.45	4.46	4.44
10-yr	3.57	3.64	3.54
5-yr	2.71	2.82	2.64
2-yr	1.55	1.73	1.45

4.3 Return Periods on a Regional Scale

4.3.1 Introduction

In Section 4.2, return periods were determined for the ACUS as a basin. This information

is useful in providing a historical context to surge events in this large, active region. On a broad

scale, quantile estimates for an entire basin provide insight into the historical magnitude of a

particularly large surge. For example, 1989's Hurricane Hugo inundated Bull's Bay, South

Carolina with a 6.1 m (20 ft) storm surge. The SRCC method places this event as somewhere in

between a 50-year and 100-year storm, and the physically calculated return period was 57 years.

The last event in the record that was equal to or greater than that magnitude occurred in 1936

(the Great New England Hurricane's 6.49 m surge,) or 53 years prior. In this case, the quantile estimation procedure is redeemed.

However, return period calculations are not always this accurate. Progressing through the record, Hurricane Andrew produced a 5.2 m (16.9 ft) surge in Miami, FL in 1992, just three years after Hugo; a 5.2 m foot surge is representative of an approximately 30-year event in this analysis. This seemingly anomalous surge event proves the inherent danger in attempting to predict natural events, especially climatological outliers. Natural extreme events are typically random processes; thus, a hurricane season that saw a 50-year surge event, for example, does not preclude the next season from having an equal or even greater surge event.

Clearly, it is not possible to predict with one hundred percent accuracy the timing of surge events. There are, though, ways to refine return periods to be a more geographically specific representation of natural processes. One method is through dividing the coast into distinct clusters, or zones, that have similar characteristics in terms of their history and vulnerability to landfalling hurricanes and associated surge events. In this section, the methods utilized in Section 4.2.2 will be applied to various coastal zones to determine quantile estimates for return periods on a local scale.

4.3.2 Methods

4.3.2.a K-Means Cluster Analysis

Many different clustering algorithms exist, each with a different set of parameters. For this analysis, the data points are not evenly distributed throughout space to adhere to a distance clustering method. Utilizing this method would result in either: (1) large stretches of coastline

that contained clusters with zero observations, or (2) a smaller number of clusters, with a few clusters containing a majority of the observations.

To avoid the problems associated with clustering based on a distance parameter, a K-means cluster analysis was implemented to produce clusters with a more even spread of data points. This method is a centroid method, which requires the user to specify a desired number of clusters, k, and splits the data into k clusters through a least-means algorithm. The K-means algorithm is iterative, and consists of two steps. The assignment step assigns each data point to the nearest mean, which are randomly placed for the first run. The update step recalculates the means to represent the new assignments. This process repeats for a specified number of iterations until each of the k clusters contains the maximum number of nearest-mean data points (McKay 2003)

The computer programming language R was utilized to produce clusters for the ACUS. R provides a package that rapidly performs many iterations, providing the user with a quick, reliable output. For this analysis the number of clusters, k, was chosen to be 10 after several test runs. The dataset contains 72 observations. To ensure that return periods of at least 20-years could be calculated for the majority of clusters, each cluster must contain greater than (n years in dataset/20) observations, or $(114/20) = 5.7$ observations. Although this should theoretically be achieved by having a maximum of $(72/5.7) = 12.6$, or 12, clusters, the spatial distribution of the dataset precludes this from happening. Because of the high concentration of events in certain areas (such as south Florida and North Carolina) and the large areas that have seen few, if any, surge events (such as from Virginia Beach north to New York City), the K-means algorithm does not provide enough events in each cluster to perform a proper analysis. In fact, the spatial distribution is so skewed that, even after dropping to $k=10$, some zones still do not contain the

requisite number of storms to produce 25-year return periods. At the discretion of the

investigator, 10 was chosen to be the final number of clusters, as this provides a 25-year return

period for most clusters while maintaining some geographic continuity across the basin. The

complete R program used to determine the clusters can be found in Appendix 2. After running

the R script, an output map was created (Figure 4.3). This map details each surge observation,

color coded with each other observation in the cluster, and cluster centroid.
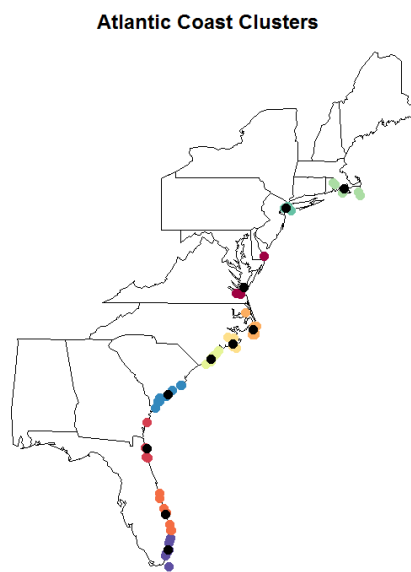
Figure 4.3: Output map from R of K-means cluster analysis. Points of same color are associated with same cluster; cluster centroids are represented by large black points.

4.3.2.b Producing Regional Quantile Estimates

The K-means output file provided by R lists the coordinates for each observation in the

dataset along with its corresponding cluster. This information allows for the creation of quantile

estimates for each zone based on the surge heights associated with each cluster. The SRCC

method was employed, as determined in Section 4.4. The number of storms in each cluster

ranged from 5 to 10. Return periods could be calculated to a level of (*n*/storms in cluster), where

n = 114 years in dataset. Each cluster contains 100-year, 50-year and 25-year surge estimates.

4.3.3 Results

Quantile estimates for each zone and the entire basin are presented in Table 4., with zone

numbers oriented from north to south along the ACUS. The zone with the highest 100-year

return period was Zone 7, centered on Charleston, SC, while the zone with the lowest 100-year

return period was Zone 2, centered on New York, NY. At each interval, Zone 7 (Charleston) has

the highest quantile estimation. Interestingly, Zone 1 (New Bedford, MA) trails Zone 7 by just

fractions of a meter at the 100-year level, but at the 25-year level has the smallest quantile

estimation. Other Zones with consistently high quantile estimates occur in geographically

expected regions, such as: Zone 5 (Morehead City, NC), Zone 6 (Wilmington, NC) and Zone 10

(Miami, FL). A graphical representation of this same data can be found in Figure 4.4.

Table 4.6: Quantile estimates for each zone. Zones calculated through a K-means analysis, quantiles calculated through SRCC method.

Zone	100-yr	50-yr	25-yr
New Bedford, MA	5.61	3.54	1.46
New York, NY	2.26	2.01	1.77
Norfolk, VA	3.44	2.71	2.01
Hatteras, NC	2.83	2.29	1.74
Morehead City, NC	4.15	3.11	2.07
Wilmington, NC	3.51	2.87	2.23
Charleston, SC	5.64	4.11	2.62
Jacksonville, FL	5.18	3.54	1.86
Ft. Pierce, FL	3.51	2.80	2.10
Miami, FL	4.91	3.66	2.38
Basin-Wide	6.55	5.67	4.79
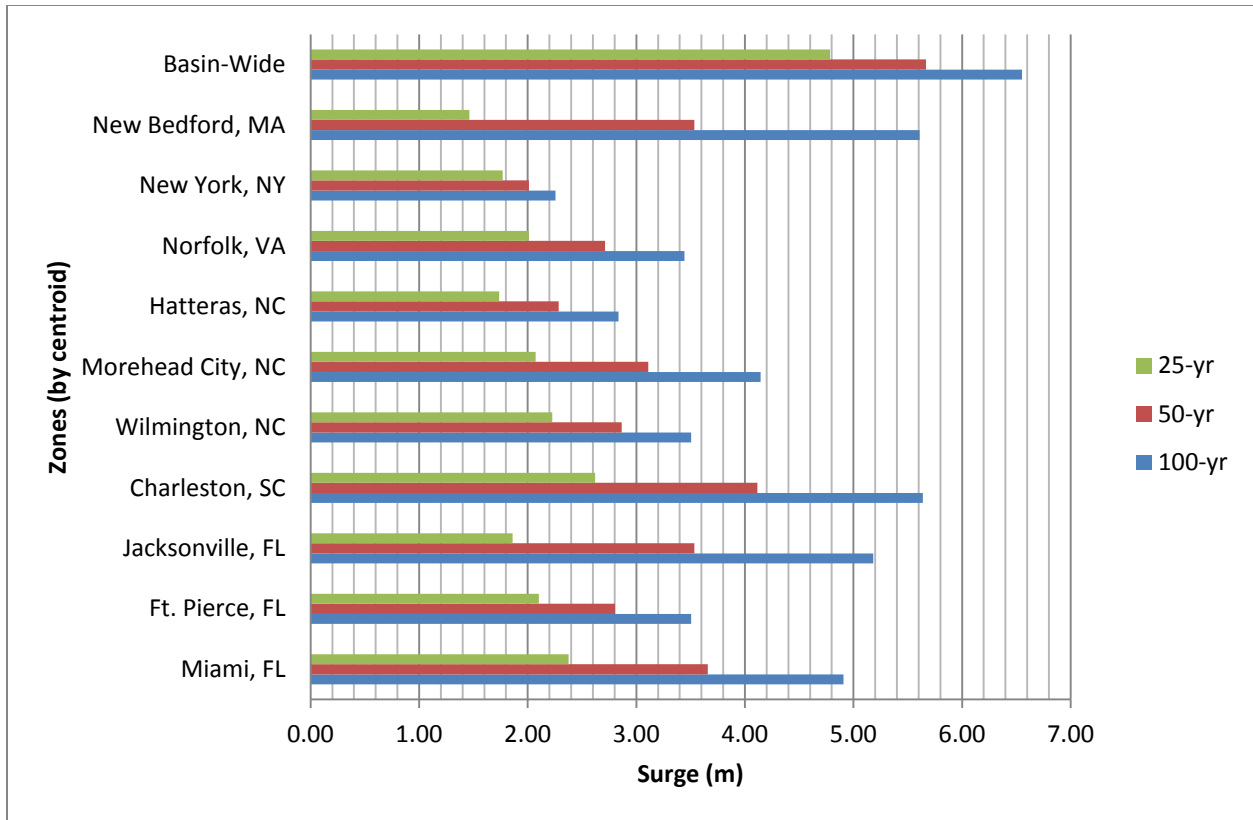
Figure 4.4: Graphical comparison of return period estimations for the entire basin and each zone for data from 1898-2011.

The quantile estimates provide a spatial context to vulnerability. These results can be applied to the K-means output map provided by R to visually describe areas historically vulnerable to surge. Observations with the same color on the output were used to manually transpose the set of points into distinct zones. For the southern portion of the study area, zone breaks were easily determined due to the high concentration of observations. Traveling northward into a less dense distribution of surge events, some discretion was required. In general, the midpoint between the northernmost point in one cluster and the southernmost point in the cluster immediately above (north) was visually determined and zones were drawn as such. This is an admittedly rudimentary procedure; however, it was deemed the best option at the time.

Zones were then color coded based on the 100-year quantile estimation. Zones with a 100-year surge of greater than 4.6 m (15 ft) were colored red; zones with a 100-year event greater than 3.05 m (10 ft) but less than 4.6 m were colored orange; and zones with a 100-year event less than 3.05 m were colored yellow. The resultant map (Figure 4.5) spatially depicts surge vulnerability. According to this analysis, Zones 1, 7, 8 and 10 have the highest 100-year vulnerability, while Zone 2 has the lowest (and represents the only zone with a 100-year event of less than 3.05 m.)

Figure 4.5: Comparison of regions based on 100-year quantile estimate. Red zones have a 100-year event > 4.6 m (15 ft); orange zones have a 100-year event > 3.05 m (10 ft) but < 4.6 m; yellow zones have a 100-year event < 3.05 m.

4.4 Discussion

Calculating return periods for a variety of geographical scales deepens understanding of vulnerability to surge. Beyond the climatological value of these analyses, stakeholders ranging from emergency management planners to individual homeowners can gain useful insight from the quantile estimates. In particular, the cluster analysis provides an excellent spatial distribution

of vulnerability. The utility of that analysis is readily apparent, and dissemination of the results is of great importance.

The most realistic interpretation of the results is achieved by taking the basin-wide quantiles in concert with the cluster anaylsis. The basin-wide 50-year event, for example, is calculated to be 5.67 m, but this number alone does not provide any context of where this event might occur. Cluster analysis helps clear up some of this uncertainty by indicating which segments of coast are most vulnerable. Two zones have a 100-year magnitude that is very close to this estimate: Zone 7 (Charleston, SC; 5.64 m) and Zone 1 (New Bedford, MA; 5.61 m). Thus, it appears more likely that the 50-year event will occur in one of these zones than in one of the other regions.

A similar clarification can be applied to the basin-wide 25-year event. This event is predicted to have a magnitude of 4.79 m. Along with the two previously mentioned zones, Zone 8 (Jacksonville, FL) and Zone 10 (Miami, FL) also have a 100-year event that exceeds this threshold (5.18 m and 4.91 m, respectively.) This lends itself to another conclusion: over the course of 100 years, each of these zones will likely receive a surge of greater than 4.79 m. It makes logical sense that the 100-year events for four zones will exceed the basin-wide 25-year event; one would expect four 25-year surge events in a 100 year time period, so it is likely that each of Zones 1, 7, 8 and 10 will exceed that threshold, while the other zones will not see surge events that exceed 4.79 m.

The application of cluster quantiles to basin-wide results seems to be a smooth one. However, digging deeper into the cluster data reveals some important caveats that must be addressed. The most important caveat is the sample size. Return periods for each zone were only

calculated to the level that the data allowed. However, when dealing with a small sample size, one outlier can skew the quantiles, especially at the lower frequency, high magnitude events. Additionally, moving into the future, one large event that supersedes the current maximum would result in a recalculation of quantiles and, likely, a change in the characteristics of the spatial distribution. On the other hand, a surge event that occurred just outside of the beginning of the dataset (for example, in 1890) and is omitted from the analysis would also change the results. It is important to note that these analyses reflect only the events that occurred within the time frame of the dataset, and cannot be taken as absolute, static measurements.

Zone 1 typifies the issue with small sample sizes. This zone contains only six surges, yet one of these surges is the largest in the dataset, the Great New England Hurricane of 1938 at 6.49 m. This event is a major anomaly, as the second highest surge in this zone is only 3.2 m, and three of the events just meet the 1.22 m threshold for inclusion in the database. As a result, the quantiles skew high at longer return periods, but very low at lower return periods. The tropical climatology of New England does not generally feature extreme events such as the hurricane of 1938. In this zone, as well as neighboring Zone 2, surge events tend to be muted, with 9 of the 10 events (excluding the 1938 outlier) having magnitudes of less than 3.05 m. Nevertheless, the large event, though atypical of this region, cannot be discounted as an event that can never occur again in the future.

The discrepancies found in Zone 1 illustrate a larger point with respect to extreme events and storm surges in particular. It is impossible to perfectly represent something as dynamic and unpredictable as extreme events through mathematical and statistical analyses. At best, the results are an approximation. This is not to discount the importance of quantile estimation in extreme event analysis, as one or two events at the tail of the distribution have a large impact on

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some return periods. Although the results are an approximation, it is reasonable to apply the results at a variety of levels. If nothing else, the discrepancies in Zone 1 prove that it is impossible to say that a certain location will never see a certain surge magnitude. Rather, these analyses provide context to surge probabilities and vulnerabilities when one views not only the quantile estimates but also the number of events in each zone. Although Zone 10 (Miami, FL) has only the fourth-highest 100-year quantile, the zone has 8 events, with three of these being greater than 3.66 m (12 ft). It is easy to make the argument that, based on these data, Miami has a much higher vulnerability to surge than New England, even if the most extreme values disagree with that claim. Thus, a full understanding of the data is necessary to make proper conclusions.

4.5 Conclusion

This chapter provided an analysis of storm surge return periods on both a basin-wide and regional scale. Data were collected following procedures outlined in Chapter 2. Return periods were calculated at the 2-year, 5-year, 10-year, 20-year, 25-year, 50-year and 100-year levels for the entire basin, and the 25-year, 50-year and 100-year levels regionally. Four different quantile estimation methods were employed, with a KS test showing that the SRCC method produced the most accurate quantile estimates.

Data were then expressed in a variety of ways. For the basin-wide data, the SRCC regression output created quantile estimates for each interval. These data reflect surge heights that can be expected to occur at some location within the basin for the specified period. A K-means cluster analysis divided each surge event into one of ten distinct zones. Quantile estimates were calculated for each zone to the level that the data allowed. Comparisons of these values in both tabular and graphical forms were created. Basin-wide surge heights ranged from 6.55 m at

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the 100-year level to 1.55 m at the 2-year level. Regionally, 100-year heights fluctuated from a high of 5.64 m in Zone 7 (Charleston, SC) to a low of 2.26 m in Zone 2 (New York, NY.)

Although the caveats discussed in Section 4.4 apply to this data, there is much utility in these calculations. By providing a spatial and empirical representation of historical storm surge events, areas of relative high and low vulnerability can be identified. A variety of stakeholders may find this information to be useful for a variety of reasons. Land managers will find this information a useful guide to projects such as beach renourishment and construction of controlling devices such as sea walls and breakwaters. Return period estimation has use to municipal leaders, as they can use these calculations as a guideline on where and how to develop coastal zones. Homeowners will also gain valuable information from the data presented in this analysis. A homeowner who loses all or part of their home in, for example, a 2.1 m surge event can consult the regional estimations to determine rebuilding procedures. A 2.1 m event in Charleston, SC is indicative of a 20-year event; thus, rebuilding in the same location is likely not a fruitful endeavor. The same event on Long Island, however, is indicative of between a 50-and-100-year event. In this location, rebuilding may be advisable. Beyond the practical uses detailed above, the data provide another layer to the fields of climatology, oceanography, environmental science, risk management and many others.

CHAPTER 5: SUMMARY, CONCLUSIONS AND FUTURE RESEARCH

5.1 Overview of Tropical Cyclone Hazards

Tropical cyclones represent one of the most heavily studied areas of climatology. Some individual natural disasters inflict comparable loss of property, economic capital or life; however, tropical cyclones synthesize each of these losses into one event. Additionally, every year from 1900-present has seen at least two tropical cyclones reach hurricane status in the Atlantic Basin (Landsea et al. 2010). Although not every year features a landfall along the Atlantic Coast of the United States (ACUS), the threat exists perennially. This high level of risk lends itself to intense scholarly research.

Tropical cyclone hazards are numerous and varied. Pease et al. (2007) found elevated levels of arsenic in eastern North Carolina following the immense flooding associated with 1999's Hurricane Floyd. Jain and Davidson (2007) determined that, especially in urban areas, current building construction and codes are insufficient in the face of strong winds associated with tropical cyclones, and expected loss values are high. Tropical cyclone-spawned tornados represent another hazard. Verbout et al. (2007) found a positive link between storm strength and incidence of tornados, and some storms, such as 2004's Hurricane Ivan, have spawned over 100 tornados.

These hazards carry some risk; however, storm surge poses the largest threat to lives and livelihoods. Individual surge events have been responsible for billions in economic loss and the deaths of thousands (Kentang 2000); (Willoughby 2012). Although storm surge events have produced the largest death and destruction tolls, the historical surge record is exceptionally under-researched. Therefore, a surge database for the ACUS was created to fill this void. The

database is a larger part of SURGEDAT, a burgeoning global database of peak storm surges associated with tropical cyclones.

5.2 Creation of a Storm Surge Database

At present, a majority of research associated with storm surge focuses on computer-based modeling, both of past events (i.e. Sheng et al. 2010) and future inundation patterns (i.e. Condon and Sheng 2012). These models provide a valuable tool and produce useful surge estimates. It is also beneficial to study historical patterns of storm surge. This information can provide context to models, and validate or disprove a simulation.

With that in mind, a peak storm surge database for the ACUS was created. Database creation comprised a large portion of research associated with this thesis, and mostly followed parameters established in Needham (2010). All events with an account of a peak surge $\geq$ 1.22 m (4 ft) were included in this dataset, for the time period of 1898-2011. To identify storms capable of producing this magnitude of surge, storm tracks compiled by Landsea (2009) and made available through the UNISYS corporation were consulted. Following parameters established in Keim et al. (2007), all storms that made landfall along or passed within an established buffer of the ACUS region were included in the initial skeleton dataset.

Once this skeleton was established, data collection began. A total of 25 sources were used to create the database; many more sources were consulted and not used, either for lack of information or information that placed the surge event below the 1.22 m threshold. Records of storm surge events, especially in the early part of the dataset (1898-1960), are not reported in a consistent manner. This raised some issues, most notably with respect to normal tidal levels. In many cases in the first half of the dataset, surge heights are given as "storm tide", which does not

distinguish between normal astronomical tide and the anomalous rise in water associated with the tropical cyclone. Thus, tidal adjustments were applied where necessary to remove the normal tidal cycle from the surge record. The result is a dataset that is homogenous in terms of the water height value recorded, and suitable for analysis.

5.3 Trend Analysis

Construction of the storm surge dataset produced 72 surge events along the ACUS producing a peak surge $\geq$ 1.22 m. An annual maximum series and annual frequency series were constructed with the resultant data. The annual maximum series, depicting the number of surge events per year along the ACUS, appears to show an increase in surge events throughout the record, with several time periods of elevated surge events (1945-1970, 1991-2011). The annual frequency series, depicting the largest peak surge event for each year, is more evenly distributed, with large surge events occurring throughout the dataset.

The events were then mapped according to several different parameters. Mapping of the full dataset revealed a few areas with a high level of activity. South Florida and the Carolinas represent the two peak areas of surge activity. Large stretches of coastline exhibit generally low levels of activity. These areas include Georgia/north Florida and the Mid-Atlantic coast, roughly from the tidewater area of Virgnia to New York City. These patterns follow spatial trends established in other studies such as Keim et al. (2007), and are likely due to the convex shape of the coast, especially in the southern half of the region, and colder ocean waters in the northern half of the region.

Surge events were also mapped according to two teleconnections: the Southern Oscillation Index (SOI), which expresses whether the Pacific Ocean is experiencing El Nino, La

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Nina or neutral conditions; and the Atlantic Multidecadal Oscillation (AMO), which expresses whether sea surface temperatures (SST) in the North Atlantic Ocean are warmer or colder than the climatological average. SOI maps produced a similar number of surge events in El Nino and La Nina years, while AMO maps showed an increase in surge events during AMO warm years.

Mapping surge events by oscillation provides some insight into spatial and climatological patterns. However, these maps do not account for surge magnitude. To determine if oscillatory phase controls surge magnitudes, a correlation analysis was performed. After determining the data was not normally distributed through a Shapiro-Wilk test, a Spearman test was performed. SOI monthly averages were tested versus surge events at three intervals: the peak of hurricane season, when the majority of the events (93%) occurred (A-S-O), and for each three-month interval dating back six months. Results were statistically insignificant at the p=0.05 level for each test, indicating no correlation between surge heights and SOI index along the ACUS. The AMO was tested for two variables: AMO index for the month of the surge event, and for the year of the surge event. These analyses also proved insignificant at the p=0.05 level, although Spearman p-values were lower than the SOI p-values. A Wilcoxon signed-rank test determined whether surge events vary in frequency based on teleconnection phase. Frequency of surge events was shown to be related to phase of the AMO at the p=0.10 level; for the SOI, no statistically significant link was discovered.

5.4 Quantile Estimates

All coastal locations have a baseline vulnerability to storm surge as a result of being located at the intersection of marine and terrestrial environments; however, this vulnerability is not homogenous. To quantify vulnerabilities for the ACUS as a whole, as well as on a regional

basis, a return period analysis was performed. The Pareto distribution along with the SRCC and Huff-Angel regression methods were employed to estimate extreme surge levels associated with 2-yr, 5-yr, 10-yr, 20-yr, 25-yr, 50-yr and 100-yr return periods. A Kolmogorov-Smirnoff test determined the SRCC method the most accurate estimation technique. SRCC quantile estimates produce a 100-yr event of 6.49 m, a 50-yr event of 5.58 m, and 2-yr event of 1.58 m.

These results provide context of expected surge events for the basin as a whole. The ACUS is more than 2000 miles in length, though, and it is useful to determine return periods for a regional basis. A k-means cluster analysis was performed to divide the region into 10 zones, each containing at least five surge events. The SRCC method was employed for each zone, and quantile estimates were produced. The analysis determined northern New England and South Carolina have the highest 100-yr quantile estimates. These results can be misleading, as one large storm influences estimates when a small sample size is used. Looking at regions that have the highest estimates of more common events, such as the 25-yr return period, provides better insight into the spatial distribution of vulnerability to surge. South Carolina remains active at this level, but New England does not. Instead, south Florida and North Carolina become more active.

5.5 Conclusions/Future Research

The analyses presented in this thesis provide some insight into storm surge activity along the ACUS. Surge events seem to be increasing in frequency throughout the record, but not necessarily in magnitude. This may be the result of an observational and recording bias. In the early part of the record, coastal regions were largely rural. These rural areas were not represented by newspapers or observers, and thus surge events that would be recorded in modern times went

unrecorded. It is difficult to discern whether the increase in frequencies is the result of a bias or natural phenomena.

Trends in frequency and magnitude with respect to the SOI and AMO yielded mixed results. SOI phase showed no significant statistical trends to magnitude, and an equal number of events for each phase. AMO phase was also insignificant statistically, but the majority of events in the dataset occurred during AMO warm years. These results indicate that AMO phase is a good indicator of the likelihood of experiencing a surge event in a given year, but not necessarily whether the event will be major or minor. With respect to spatial vulnerability determined by quantile estimates, South Florida and the Carolinas exhibit the highest vulnerabilities in that they tend to experience a higher frequency of moderate-to-large surge events. New England features a high 100-yr return period, but very low return periods at shorter scales. This is the result of an anomalously large surge event in this region, the 1936 surge event that produced a 6.5 m surge event. This event is not typical of the region, with no other events greater than 3.2 m, and results in a 100-yr estimate that might, should the record be expanded, be more indicative of a 500-yr event in this region.

The research presented in this thesis contains a few caveats. As mentioned, the early part of the dataset is sparse, with events increasing with time. This observational bias is difficult to avoid when dealing with historical data, and must be accepted as a limitation of this study. The small sample sizes of the zones created by the k-means analysis skews the quantile estimates in some cases, as discussed in the case of New England. This problem can be averted by examining shorter return periods to determine areas that have received a large number of events through the record.

This research contributes to SURGEDAT, a global database a peak storm surges. The completion of this research concludes peak surge analysis for the areas of the United States that are most vulnerable to surge (the ACUS and Gulf of Mexico). Research is ongoing to include every surge event ≥ 1.22 m on a global scale, and this research should proceed in order for SURGEDAT to truly be considered a global database.

It is also important that SURGEDAT be maintained through time. Each successive hurricane season has the potential to produce more surge events, and these events must be added to SURGEDAT. Re-analysis of trends should be completed after each season with new surge events, especially the quantile estimates. As is the nature of extreme event analysis, one large event can change quantile estimates substantially. A longer time series and increase in surge events will only improve the accuracy of the methods described in this thesis.

Research should also be expanded to include not only peak surges, but all surge records for each storm. This is obviously a time consuming task, and for the majority of the dataset, this data simply does not exist. In modern years, as the National Oceanic and Atmospheric Association and the US Army Corps of Engineers have compiled comprehensive storm reports, an envelope of surge heights can be produced. This type of analysis will provide a better context of vulnerability, as a tropical cyclone can produce large surges for a wide stretch of coast and not just at one location.

Finally, further investigation into connections between surge frequency and magnitude and climate teleconnections will aid in surge prediction as well as computer-based model development. Along with the AMO and SOI, indices such as the North Atlantic Oscillation

(NAO) and Quasi-Biennial Oscillation (QBO) may provide insights into large scale factors

controlling storm surge.

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APPENDIX 1: METADATA FILE CONTAINING ALL SURGE INFORMATION

Storm: Unnamed
Year: 1898
Dates: Sept 25-Oct 5
Max Surge Height: **5.49 m (18 feet)** at Sapel's Lighthouse, GA, 10/1/98
Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1898.pdf
Source 1 text: p440 - "At Isle of Hope the water rose 15 feet, washing out bath houses and boat houses....At Tybee Island, Mr. Lovell's house was blown away, and at the port about 24 feet of sand piled up inside the works. At Warsaw the barracks were washed out, and a depth of 4 feet of water was reported in the magazine. The Sea Islands off the Carolina coast escaped severe injury, although the tide was very high and the wind heavy. At Beaufort the water came up into the streets....At noon on the 2d, the principle residence and business thoroughfares (in Brunswick) were 4 to 8 feet under water....Campbell Island, 12 miles from Darien, on the Attahama, was swept by water and all of its inhabitants except 3 drowned..the height of the tidal wave at that place (Darien) was 13 feet above mean high water mark and 18 feet at Sapel's Lighthouse."

Storm: "Hurricane San Ciriaco"
Year: 1899
Dates: Aug 4-Sept 4
Max Surge Height: **3.05m (10ft),** Hatteras, NC, 8/17/99
Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1899.pdf
Source 1 text: The hurricane was the most severe in the history of Hatteras. The scene on the 17th was wild and terrific. By 8AM the entire island was covered by water from the sound, and by 11AM all the land was covered to a depth of 4-10 feet…There were not more than 4 houses on the island in which the tide did not rise to a depth of 1 to 4 feet, and at least half the people had to abandon their homes..

Google Earth puts all of Hatteras, NC <4ft elevation, save for dunes. Assuming the low end of 4-10 feet occurs in the highest elevation areas (which are also further from the sound), those tides are likely around 8ft. Land slopes to sea level towards sound, which probably increases amount of water inundation. Thinking an 8 ft tide.

Storm: Unnamed
Year: 1903
Dates: Sept 9-16
Max Surge: **1.52 m (5 feet)** at Jupiter, 9/11/03

Source 1: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 1 text: Table4 on p 90 lists surge at 8-10 ft. Where?
Source 2: Florida's Hurricane History by Jay Barnes
Source 2 text: "The storm surge was about eight feet at Jupiter and ten feet at Apalachicola"
Apalachicola on the Panhandle. Atlantic surge = 8ft

Tidal Adjustment: 3 foot tide at landfall time. 8-3=5 foot surge event

Storm: Vagabond Hurricane
Year: 1903
Dates: Sept 12-17
Max Surge Height: **1.95 m (6.4 ft)** at Battery Park, NY on 9/16/03

Source 1: New York Times, page 2, 9/17/03
Source 1 text: "The highest tide which has been recorded in several years was noted by the Dock Department yesterday. The water rose 6.4 feet, while the high record is 6.8 feet. The seawall at the Battery was completely under water when the tide reached its peak. All during the storm the water, driven by the wind, struck the wall, and then, dashing up, was carried into the street across Battery Park."

Storm: Unnamed
Year: 1906
Dates: Oct 8-23
Max Surge: **2.13 m (7 feet)** at St. Augustine, FL, 10/18/1906

Source 1: Florida's Hurricane History by Jay Barnes
Source 1 text: "Initial reports from Miami stated that the telegraph office was flooded by two feet of water.." "Damage was reported at Jupiter, which had 70mph winds, and at St. Augustine, which had its highest storm tide in ten years."
Source 2: http://news.google.com/newspapers?id=ZLUgAAAAIBAJ&sjid=cmkFAAAAIBAJ&pg=1534%2C4359317
Source 2 text: At St Augustine, the tide was the highest in 10 years and streets along the bay front inundated.

St Augustine bay front sits at a max elevation of 7ft, per Google Earth. Will go with that.

Storm: Unnamed
Year: 1911
Dates: Aug 23-31
Max Surge Height: **1.8 m (5.9 ft)**, Charleston, SC, 8/27/11
Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1911.pdf
Source 1 text: After the high tide on the morning of the 27th, the sea began to rise and at the high tide that night reached a point of 10.6 feet above mean low water.
Source 2: Low Country Hurricanes, by Walter J. Fraser, Jr.
Source 2 text: The storm tide rose to nearly 11 feet, slightly less than the record set during the hurricane of 1893.

Tidal adjustment: 4.7 ft tide at landfall time. 10.6-4.7= 5.9 ft tide

Storm: Unnamed
Year: 1914

Dates: Sept 15-19
Max Surge Height: **1.52 m (5 ft)** at St. Augustine, FL on 9/16/14
Source 1: http://www.aoml.noaa.gov/hrd/hurdat/metadata_master.html

Source 1 text: The northeast of Wednesday [16th] raised some water around St. Augustine, causing the tide to come in so high that it ran over the South Street Causeway, and tons of dead grass were
washed away from the marshes about the city.

South St. Causeway is roughly 5 feet above sea level, so put this at a 5 foot tide.

Storm: Unnamed
Year: 1918
Dates: Aug 23-26
Max Surge Height: **2.47 m (8.1 ft)** at Lumina, NC on

Source 1: Wilmington Morning Star, 8/25/18
Source 1 text: "The southern end of the beach, near Lumina, bore the brunt of the storm…the steps and part of the pavilion on the sea side of the Lumina were washed into the sea. Also the moving picture screen over the waves was blown away."
"The second section of the pier at the Seashore hotel went down before the storm at 11:30…..During the hardest part of the gale, the waves rose over the pier, and its steel supports were unable to stand the force of the breakers. The small wooden balcony at the end of the pier was first washed away and was followed a few minutes later by the section between the two observation houses built out over the surf."
"AT ten oclock, when the tide was the highest, the surf extended up the beach to the pavilion at the Seashore….near the Hicks cottage, the surf broke through and lapped over into the high water from the sound. The tide rose to the boardwalk at the Oceanic hotel

Unable to track down location of Hicks Cottage. however, the general highest point in this area of coast is roughly 12 ft, on the dunes right on the shore. This was only a Cat 1, so 12 ft tides seem unlikely. It is likely that these dunes were not constructed or built up to the point they are today in 1918. The remainder of the island has a peak elevation of ~10 feet. Seems high, but considering the waves took down a pier, seems like it could be possible.

Tidal adjustment: 1.9 ft tide at landfall time. 10-1.9=8.1 foot tide

Storm: "Great Miami"
Year: 1926
Dates: 9/18/1926
Max Surge Height: **3.75 m (12.2 feet)** at Coconut Grove, FL on 9.18.1926

Source 1: http://www.nhc.noaa.gov/HAW2/english/history.shtml#new
Source 1 Text: A storm surge of nearly 15 feet was reported in Coconut Grove.

Source 2: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1926.pdf
Source 2 Text: The tide ranged from 7.5 ft along the northern part of the Miami water-front to 11.7 ft along the lower water-front of the Miami River. (above mean low water)
Source 3: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 3 text: Table 4 on p91 lists surge of 13.2ft in Miami
Source 4: Florida's Hurricane History by Jay Barnes
Source 4 text: "At least eight inches of rain fell, and a storm surge taht measured 11.7 feet above mean low water struck Biscayne Boulevard. Gray estimated the surge in Coconut Grove to have been 14 or 15 feet, and called it 'the greatest ever caused by a storm on the coast of the United States.' The waterfront in Miami was flooded two to three blocks from the bay, and most sections near the Miami River were under several feet of water."

Tidal adjustment: 2.8 ft tide at landfall time. 15-2.8 = 12.2 ft surge

Storm: Unnamed
Year: 1926
Dates: July 22-Aug 2
Max Surge Height: **2.26 m (7.4 ft)** at Merritt Island, FL on 9/28/1926

Source 1: Florida Hurricanes and Tropical Storms, 1871-2011 by John M Williams
Source 1 text: "The high winds and seas swept before them boats, docks, boat houses and other marine property on the ocean front as well as that on the Indian River Lagoon….the observer at Merritt Island remarks that there was a tremendous wave and with the high wind all boats, docks and other property from the river front were swept ashore." From US Weather Bureau

River front on Merritt has a steep gradient from 0 up to around 8ft not very far inland, per Google Earth. If surge was enough to sweep river property ashore, surge must have reached up to the 8 ft level.

Tidal adjustment: 0.6 ft tide at landfall time. 8-0.6 = 7.4 ft tide.

Storm: Unnamed
Year: 1928
Dates: Aug 3-12
Max Surge Height: **3.35 m (11 ft)** at Ft. Pierce, FL on 8/8/1928

Source 1: Florida's Hurricane History by Jay Barnes
Source 1 text: "Substantial houses were unroofed and frail ones were razed. Highways were flooded and badly washed. Many bridges were undermined requiring replacement."

Seems to be a lot of highways in Ft Pierce that sit at roughly 10-12 ft above MSL. Some are up to 25 ft above, but doubt the tide would have reached that high to overwash them. Additionally, 10-12 ft is probably enough to undermine a bridge. Split the difference and went with 11 ft.

Storm: Okeechobee Hurricane
Year: 1928
Dates: Sept 6-20
Max Surge Height: **3.2 m (10.5 ft)** at Palm Beach, FL on 9/16/1928

Source 1: Low Country Hurricanes by Walter R Fraser
Source 1 text: "winds at Georgetown reached fifty miles per hour and high tides covered the city docks, flooding ruined goods stored in warehouses."
Source 2: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 2 text: from Table4 on p91, 10-15 ft. Where?
Sourcd 3: Florida's Hurricane History by Jay Barnes
Source 3 text: "Experiencing the awesome power one would expect from a Category 4 storm, Palm Beach County was rocked by a large tidal surge and winds estimated at over 150mph."
Source 4: Encyclopedia of Hurricanes, Typhoones and Cyclones by David Langshore
Source 4 text: "Steady fringe rains were already falling in Fort Lauderdale (on the 16th), while enormous breakers - some 15 feet hight - splashed ashore at Pompano Beach."
Source 5: http://www.hurricanecity.com/city/palmbeach.htm
Source 5 text: September 16th,over 2500 killed from flooding bar 27.43 winds 150mph over 18 inches of rain very heavy damage,most killed around Lake Okeechobee. Storm surge on coast estimated at 11ft killing 25 & washing out A1A

10-15 ft from Williams is a good range. We have a 15ft estimate and an 11ft estimate. Storm made landfall justa bout at Palm Beach, which means the highest tide would likely have been there, not at Pompano. Will go with a 12ft surge at Palm Beach as the highest to split the difference.

Tidal adjustment: 1.5 ft tide at landfall time. 12-1.5 = 10.5 ft tide.

Storm: Chesapeake-Potomac Hurricane
Year: 1933
Dates: Aug 17-26
Max Surge Height: **2.99 m (9.8 ft)** at Sewells Point, VA on 8/23/33

Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1933.pdf
Source 1 text: A tide of 7 ft above normal occurred, flooding the downtown business district of Norfolk as never before.
Source 2: Encyclopedia of Hurricanes, Typhoones and Cyclones by David Langshore
Source 2 text: "In several places along the western edge of the Chesapeake Bay, the hurricane's 10-foot storm tide dragged beachfront cottages from their foundations, stranded sleek sailboats and boxy motor yachts on tidal mud flats, and inundated much of downtown Norfolk with 6 to 8 feet of brackish water. The town of Gloucester Point, 30 miles northwest of Norfolk, saw both its post office and drugstore leveled by the hurricanes 30 foot waves."
Source 3: http://www.newpointcomfort.com/history/history_html/33_storms.html
Source 3 text: This storm produced a record tide of 9.8 feet above mean lower low water at Sewells Point. Norfolk saw a tide of 9 feet above mean low water. Five feet of water flooded the

city, damaging area crops. A six to nine foot storm surge passed up the Chesapeake Bay. A combination of the storm's surge and back water flooding caused crests as high as 12 feet above mean low water. At least ten vessels met their fate in the hurricane.

Storm: Unnamed
Year: 1933
Dates: Sept 8-21
Max Surge Height: **2.53 m (8.3 ft)** at Sewells Point, VA on 9/16/33

Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1933.pdf
Source 1 text: Great damage was done by wind and high water in New Bern and vicinity….Water reached a height of 3-4 feet in some of the streets which is about 2 feet higher than the previous record.
Source 2: North Carolina's Hurricane History by Jay Barnes
Source 2 text: "In the down east community of Merrimon, the tide was estimated at "fifteen or sixteen feet". Only four out of thirty houses remained after tides overwashed the area."..."At nearby Cedar Island, about eight families endured the hurricane, and almost all of their homes were washed off their foundations or severely damaged."

Source 3: http://www.hpc.ncep.noaa.gov/research/roth/vaerly20hur.htm
Source 3 text: Heavy damage was seen with this storm in Virginia. Winds rose to 75 mph at Hampton Roads, 87 mph at Cape Henry, and 88 mph at Norfolk Naval Air Station. Tides reached 8.3 feet above mean lower low water at Sewells Point. This hurricane reshaped the peninsula where New Point Comfort lighthouse stood into an island.

Highest tides likely in VA (8.3ft)

Storm: Unnamed
Year: 1934
Dates: May 27-31
Max Surge Height: **1.22 m (4 ft)** at Beaufort, SC, 5/29/1934

Source 1: Low Country Hurricanes by Walter R Fraser
Source 1 text: "[on Edisto Island] breakers as high as palmetto trees crashed across the spit of sand where the village of Edingsville Beach had once stood. At Folly Beach, winds swept waves fifty feet beyond the high water mark, wrecking five houses and seriously damaging twenty seven others.

Breakers as high as palmetto trees must be an anecdotal exaggeration, because Palmettos are extremely tall. Using google Earth to identify current homes that are 50 feet from the edge of the beach results in some houses being in that range. These homes are roughly 10 feet above MSL. They are 6ft above the high tide line on the map. High tides for a C1, but with the Palmetto tree story, I supposed tides could have been that high. Will temper the tides to 7 feet for now due to ambiguity of account (skew towards 6ft rather than 10ft due to relative weakness of storm), but

would really like to get another account of this storm.

Tidal adjustment: 3 ft tide at landfall time. 7-3 = 4 ft surge.

Storm: Unnamed
Year: 1935
Dates: Oct 30-Nov 8
Max Surge Height: **2.43 m (8 ft)** at Ft. Lauderdale, FL on 11/4/35

Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1935.pdf
Source 1 text: No reports of any extremely high tide in connection to this storm has been received. At Miami, a tide of 5ft, 2.2 ft above mean sea level was reported at 2PM, about 15 minutes after the passage of the calm center. At Pigeon Key in Biscayne Bay, an estimated reading of almost 6 ft was made. A high tide was reported at Fort Lauderdale following the axis of the storm center and wind shift from the northwest to easterly, but details are lacking.
Source 2: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 2 text: From Table4 on p92, 6ft in Miami
Source 3: Florida's Hurricane History by Jay Barnes
Source 3 text: "Along the (Miami) waterfront, storm tides caused damage to docks, marinas and low-lying structures. At Miami Beach tides were more thatn six feet above normal;at Fort Lauderdale they measured about eight feet above normal high water."

Storm: Unnamed
Year: 1936
Dates: Sep 8-25
Max Surge Height: **2.83 m (9.3 ft)** at Sewells Point, VA on 9/18/36

Source 1: http://www.hpc.ncep.noaa.gov/research/roth/vaerly20hur.htm
Source 1 text: This storm was one of the most severe in the history of Cape Hatteras. Norfolk experienced severe flooding. The highway from Currituck to Norfolk was washed out by heavy rains. Buena Vista along the James River set a record crest (22 feet), as did Westham (23.4 feet). Maximum sustained winds reached 68 mph at Hampton Roads and 84 mph at Cape Henry, before the anemometer failed. Tides rose to 9.3 feet above normal water at Sewells Point. (Norfolk)
Source 2: North Carolina's Hurricane History by Jay Barnes
Source 2 text: "Many roads and highways [at Nags Head] were covered with water and sand, and bridges were undercut by the tides. The hgihway from Currituck to Norfolk was washed out, hampering relief efforts after the storm."

Storm: "Great New England"
Year: 1938
Dates: Sept 10-22
Max Surge Height: **6.49 m (21.3 ft)** at Fairhaven, MA on 9/21/1938

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1938.pdf
Source 1 Text: [287]
At Blue Hill Observatory, Milton, Mass., the maximum 5-minute velocity was 121 miles an hour and for shorter intervals the wind velocity was indicated to be 173 for one measurement and 183 for another. At the observatory on Mount Washington the 5-minute maximum was 136.
Along the shores of Long Island and New England, rises of water caused by the hurricane winds exceeded all records at a number of points.
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THE INUNDATION
Damage to property along the coast was largely due to the storm wave. At Sandy Hook the tide was 8.2 feet above mean low water; at the Battery, New York City, it was 6.44 feet above mean sea level. Along the coast of Connecticut, Rhode Island, and on the shores of Naragansett and Buzzards Bays, the highest tide ranged from 12 to 25 feet above mean low water, being highest on the southern shores of Massachusetts, where the maximum stage occurred about 5 or 6 p.m. At Point Judith Coast Guard Station the water rose 18 feet above mean low water; at Fairhaven it was estimated at 25 feet; at Pocasset, 20 feet; at the Nobska Point Light Station, 15 feet. At Fall River it was reported that "the water came up rapidly in a great surge," the crest being estimated at "18 feet above normal."
The storm tide, combined with the hurricane winds, raised havoc with small craft and was very destructive to harbor, resort, and beach property.
DAMAGE AND LOSS OF LIFE
The American Red Cross reported on October 27 that 488 lives were lost in the hurricane, 100 persons were missing, 1,754 were injured more or less severely and 93,122 families had suffered more or less serious economic losses. The number of summer dwellings destroyed was placed at 6,933, and other dwellings at 1,991. Boats destroyed numbered 2,605, barns 2,369, and other buildings 7,438.

Source 2: http://www.nhc.noaa.gov/HAW2/english/history.shtml#new
Source 2 Text: Blue Hill Observatory, Massachusetts measured sustained winds of 121 mph with gusts to 183 mph (likely influenced by terrain). A U.S. Coast Guard station on Long Island measured a minimum pressure of 27.94 in. Storm surges of 10 to 12 ft inundated portions of the coast from Long Island and Connecticut eastward to southeastern Massachusetts, with the most notable surges in Narragansett Bay and Buzzards Bay. Heavy rains before and during the hurricane produced river flooding, most notably along the Connecticut River.

Source 3: Encyclopedia of hurricanes, typhoons, and cyclones by David Langshore
Source 3 text: "the Long Island hurricane released 130 MPH (209KPH) winds, 186 MPH (299KPH) gusts, and a 21 foot (7m) storm tide on the entire southwest coast of the Island."

Source 4: http://www.hurricanecity.com/city/providence.htm
Source 4 text: 85mphSept 22nd, 60 miles to the west 600 killed near this areas as they had gusts over 130mph press 27.94.Very high storm surge up to 30 ft,16 ft reported in Providence. System was moving at a forward speed of 38mph when it hit.

Source 5: http://www2.sunysuffolk.edu/mandias/38hurricane/weather_history_38.html

Source 5 text: The hurricane hit Long Island around 3:30 PM which was just a few hours before astronomical high tide. At this time the eye was about 50 miles across and the hurricane was about 500 miles wide (Francis, 1998). High tide was even higher than usual because of the Autumnal Equinox and new moon. Combined with winds gusting over 180 mph, few on eastern Long Island's south shore had a chance when the storm surge hit. Waves between 30 and 50 feet pounded the coastline with millions of tons of sea water, sweeping entire homes and families into the sea. The impact of the storm surge was so powerful that it was actually recorded on the earthquake seismograph at Fordham University in New York City (Francis, 1998). Most people did not even realize that a hurricane was upon them even as the waters began flooding their coastal homes. The hurricane produced storm tides of 14 to 18 feet across most of the Long Island and Connecticut coast, with 18 to 25 foot tides from New London east to Cape Cod. The destructive power of the storm surge was felt throughout the coastal community. Downtown Providence, Rhode Island was submerged under a storm tide of nearly 20 feet while downtown Westhampton Beach, a mile inland, was under 8 feet of water! Sections of Falmouth and New Bedford, Massachusetts were also submerged under as much as 8 feet of water.

Source 6: Hurricanes of the North Atlantic: Climate and Society by James Elsner
Source 6 text: The worst hurricane disaster in the northeast occurred in September, 1938. The storm surge brought water to a depth of 3m into downtown Providence.

Tidal adjustment: 3.7 ft tide at landfall time. 25-3.7 = 21.3 ft tide

Storm: Unnamed
Year: 1940
Dates: Aug 5-15
Max Surge Height: **3.44 m (11.3 ft)** at Lady's Island, SC, 8/11/40

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1940.pdf
Source 1 text: Tides were very high north of the center, Charleston reported 10.7 feet above mean low tide.
Source 2: Low Country Hurricanes by Walter R Fraser
Source 2 text: "A storm surge of thirteen feet rolled over St Helena Island and Lady's Island."…also at Folly's Island
Source 3 : Encyclopedia of Hurricanes, Typhoones and Cyclones by David Langshore
Source 3 text: ""In August 1940, an unnamed Category 2 hurricane pounded Savannah and its environs with 105MPH winds, scudding rains, and a 9foot storm surge."

Tidal adjustment: 1.7 ft tide at landfall. 13-1.7 = 11.3 ft

Storm: Unnamed
Year: 1944
Dates: Oct 12-23
Max Surge Height: **3.23 m (10.6 ft)** above low water, Jacksonville Beach, FL, 10/19/44;

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1944.pdf
Source 1 text: (Surge heights can be found in Table 2 of the Monthly Weather Review's special section of this hurricane.)
Source 2: Low country Hurricanes by Walter R Fraser
Source 2: " Winds gusting at sixty five mph and a nine foot tidal surge did comparatively little damage at Charelston, though the storm wrecked the piers of the Charleston Yact Club.."
Source 3: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 3 text: From Table4 on p 93, 12.3 ft in Jacksonville.
Source 4: Florida's Hurricane History by Jay Barnes
Source 4 text: "It is intersting to note that the hurricane's highest tides in Florida were not on the southwest coast near the place of landfall but on the northeastern beaches where the storm made its exit from the state. Gale-force winds from the ATlantic piled water along the shore from Cocoa Beach, where a causeway was washed out, to Savannah. The storm's highest tide was recorded at Jacksonville Beach -12.28 feet above mean low water. In some areas, beach earosion extended 150 feet."

Tidal adjustment: 1.7 ft tide at landfall time. 12.3-1.7 = 10.6 ft tide

Storm: Unnamed
Year: 1944
Dates: Sep 9-16
Max Surge Height: **3.2 m (10.5 ft)** at Providence, RI on 9/15/44

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1944.pdf
Source 1 text: (Surge heights can be found in Table 3 of the Monthly Weather Review's special section of this hurricane.)

Source 2: Wilmington Morning Star, 9/15/44
Source 2 text: "Famous piers in Atlantic City and other Jersey resorts were damaged by waves described by coast guards as the mightiest they had ever seen and sections of boardwalk were swept inland or carried away....the Homestead Restaurant on the Ocean City, NJ boardwalk near Asbury Park was washed into the sea.....a pier was washed out at Asbury Park, but details were unavailable."

Tidal adjustment: 1.5 ft tide at landfall time. 12-1.5=10.5 ft surge

Storm: Unnamed
Year: 1945
Dates: Sep 12-20
Max Surge Height: **3.66 m (12 ft)** at Cutler Ridge, FL on 9/15/1945

Source 1: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 1 text: from Table4 on p93, 13.7 ft at Homestead (?)

Source 2: Florida's Hurricane History by Jay Barnes
Source 2 text: "High tides also battered the area, and large waves rolled over the local beaches. Tides at Miami Beach were 4.5 feet above mean low water; portions of Miami saw flooding up to 10.7 feet; and at Cutler Ridge, about fifteen miles south of Miami, the storm surge rose 14 feet above mean low water."
Source 3: http://www.hurricanecity.com/city/miami.htm
Source 3 text: sept 15th,140mph from the ESE homestead a.f.b hit with gusts to 170mph ,Miami had a 10.7 ft storm surge ,Miami bch 4.5 ft hurricane hit near florida city with wind gusts from 135 to 171mph 1,000 homes badly damaged,calm reported for 1 hour

Tidal adjustment: 2 ft tide at landfall time. 14-2 = 12 ft surge

Storm: "George"
Year: 1947
Dates: Sep 4-21
Max Surge Height: **2.29 m (7.5 ft)** at Boynton Beach,FL on 9/17/1947

Source 1: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 1 text: From Table4 on p93, 21.6ft at Clewistown. This is a huge surge, but this was a Cat5 at landfall, so could be accurate.
Source 2: Florida's Hurricane History by Jay Barnes
Source 2 text: "Wind-driven water once again flooded much of the southwestern Gulf coast. Tides at Everglades City were 5.5. feet above mean low tide....Flooding also affected areas other than the Florida coastline. Even though the dikes on Lake Okeechobee held, tides measured 21 feet at Clewiston and Moore Haven.
Serious flooding also plagued the cities on the east coast that caguht the brunt of the storm. Weather Bureau records indicate that a mximum tide at Hillsboro Lighthouse of 11 feet above mean low tide was maintained for thirty minutes. Tides of 11 feet were also reported along the coast from Fort Lauderdale to Palm Beach."
Source 3: http://www.hurricanecity.com/city/deerfield.htm
Source 3 text: sept 17th,155mph measured bar 27.97 inch severe damage in this area storm surge 11ft 121mph for 5 min a very slow moving storm pounded the area for hours,causes 51 deaths,a very large & intense storm

Put max tide around Boynton Beach, because storm came ashore near Boca Raton, and this is slightly north of landfall. 11 feet.

Tidal adjustment: 3.5 ft tide at landfall. 11-3.5=7.5 ft surge.

Storm: Unnamed
Year: 1947
Dates: Oct 9-16
Max Surge Height: **3.17 m (10.4 ft)** at Parris Island, SC on 10/15/47

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1947.pdf
Source 1 text: High tides along the Georgia and South Carolina coasts ranged from 12 ft above mean low tide at Savannah Beach, GA and Parris Island, SC, to 9 ft at Charleston and 9.6 ft at St. Simons Island near Brunswick, GA
Source 2: http://www.hurricanecity.com/city/deerfield.htm
Source 2 text: oct 12 from the SW 85mph gusts to 92mph heavy rain,21 ft storm surge

Tidal adjustment: 0.6 ft tide at landfall time. 12-0.6 = 10.4 ft surge.

Storm: "Delray Beach Hurricane"
Year: 1949
Dates: Aug 23-31
Max Surge Height: **2.1 m (6.9 ft)** at Palm Beach, FL on 8/27/1949

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1949.pdf
Source 1 text: The water of the lake rose 12 feet or more at places on the southeast and east side of the lake, but the levees held and there was no flooding from the lake.
NOTE: DOES LAKE SURGE = STORM (OCEAN)SURGE??
Source 2: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 2 text: From Table 4 on p 93, 24 ft at Belle Glade.
Source 3: Florida's Hurricane History by Jay Barnes
Source 3 text: "High tides lifted piers and fish houses off their pilings and tossed them onto the shore. At Palm Beach, the storm surge carried sand into the streets and left wreckage piled high."
Source 4: Miami Herald, 8/27/49
Source 4 text: "Waves up to eight feet in height pounded seawalls along the Gold Coast and piled up water in the intercoastal waterways."
Source 5: http://www.hurricanecity.com/city/palmbeach.htm
Source 5 text: August 26th 1949 150 mph meter blew away,eye passes over palm beach. Lake okeechobee 12 ft storm surge.

Using Palm Beach as surge point due to track of storm.

Tidal adjustment: 1.1 ft tide at landfall time. 8-1.1 = 6.9 ft surge.

Storm: King
Year: 1950
Dates: Oct 13-19
Max Surge Height: **1.52 m (5 ft)** at Miami Beach, FL on 10/18/50

Source 1: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 1 text: From Table 4 on p 94, 19.3 ft at Clewiston (Lake Okeechobee)
Source 2: Florida's Hurricane History by Jay Barnes
Source 2 text: "In Miami Beach many streets were buried deep in sand...flooding was more than two feet deep in some locations. At the Macfadden-Deauville Hotel, water was more than six

inches deep in the lobby." "The hurricane's lashing tides eroded seawalls and battered oceanfront properties all along Florida's eastern shore...Angry tides ripped away city docks and fish houses at Indian River and Titusville, and the seawalls at Cocoa Beach collapsed. Causeways and bridges were washed out in at least four counties, and small craft were scattered and sunk."

Hotel lobby is at 5 ft, per Google Earth. Thus, 5 foot surge.

Storm: Carol
Year: 1954
Dates:
Max Surge Height: **2.99 m (9.8 ft)** at Bristol, RI on 8/31/1954

Source 1: http://www.nhc.noaa.gov/HAW2/english/history.shtml#new
Source 1 Text: Storm surge flooding occurred along the New England coast from Long Island northward, with water depths of 8 to 10 ft reported in downtown Providence, Rhode Island.

Source 2: North Carolina's Hurricane History by Jay Barnes
Source 2 Text: "Gusts were recorded to 65 mph at Cherry Point and 55 mph at Wilmington. Tides ran from three to five feet above normal."...."Tides at Providence (RI) were eight to ten feet above normal"

Source 3: Encyclopedia of hurricanes, typhoons, and cyclones by David Langshore
Source 3 text: An intense category 2 at first landfall on central Long Island, Carol's 125MPH gusts, scouring rains and 12 foot seas toppled huge elm trees at East Hampton, washed out roads on the west end of the island and stranded 4500 people in the town of Mantauk."

Source 4: http://www.hurricanecity.com/city/longislandny.htm
Source 4 text: Aug 31st 95mph hurricane Carol hits Eastern long island as many homes were splintered by gusts to 130mph in August. A pressure of 960mb 28.33inch in Suffolk as the hurricane approached at 47mph NNE. A storm surge of 6.1 ft was observed. Recon mission was flown just hours before landfall. A gust of 135mph recorded on block island.

Source 5: http://www.hurricanecity.com/city/providence.htm
Source 5 text: Carol Aug 31st 90mph just west while moving NNE with gusts to 130mph press 28.75 heavy damage from storm surge.200 homes destryed in Newport to the south & 60 killed. A storm tide of 14.8ft was observed. After this hurricane a wall was built to protect from storm surges.

Source 6: "Southern New England Tropical Storms and Hurricanes, A Ninety-eight Year Summary 1909-1997", by David R. Vallee and Michael R. Dion, National Weather Service, Taunton, MA.
Source 6 text: Hurricane Carol arrived shortly after high tide, causing widespread tidal flooding. Storm surge levels ranged from 5 to 8 feet across the west shore of Connecticut, and from 10 to 15 feet from the New London area eastward. Storm tide profiles show, as in 1938, how dramatically the tides increased just before landfall across Narragansett Bay, the Somerset,

Massachusetts area and in New Bedford, Massachusetts Harbor. Narragansett Bay and New Bedford Harbor received the largest surge values of over 14 feet in the upper reaches of both water ways. On Narragansett Bay, just north of the South Street Station site, the surge was recorded at 14.4 feet, surpassing that of the 1938 Hurricane. However, since Hurricane Carol arrived after high tide, the resulting storm tide was lower.

Tidal adjustment: 4.6 ft tide at landfall time. 14.4-4.6=9.8 ft surge

Storm: Hazel
Year: 1954
Dates: October 5-18
Max Surge Height: **4.54 m (14.9 ft)** at Atlantic Beach, NC on 10/15/1954

Source 1: http://www.nhc.noaa.gov/HAW2/english/history.shtml#new
Source 1 Text: Hazel turned north and accelerated on October 15, making landfall as a Category 4 hurricane near the North Carolina-South Carolina border.
A storm surge of up to 18 ft inundated portions of the North Carolina coast.

Source 2: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1958.pdf
Source 2 Text: If the storm center had moved inland south of Cape Fear on a northwestward or northward trajectory, the accompanying tides might have exceeded the 16 feet of Hazel. [Note: this source provides a peak surge of 16 feet for Hazel. Other source(s) provide a surge height of 18 feet]
Source 3: North Carolina's Hurricane History by Jay Barnes
Source 3 text: "The storm surge that Hazel delivered to the southern beaches was the greatest in North Carolina's recorded history. The flood reached eighteen feet above mean low water at Calabash. Hazel's surge was made worse by a matter of pure coincidence - it had struck at the exact time of the highest lunar tide of the year - the full moon of October...Hazel's storm tide may have been boosted several feet by the unfortunate timing of its approach."...."In Atlantic Beach, Hazel's storm surge pounded the boardwalk area to rubble. Twenty foot waves washed away a section of the Atlantic Beach Hotel. On the other end of the boardwalk, waves washed through the lobby of the Ocean King Hotel, undermining the structure" **Good pic on p 102**
Source 3: Encyclopedia of Hurricanes, Typhoones and Cyclones by David Langshore
Source 3 text: "the worst of South Carolina's October hurricanes, Hazel, barreled ashore at North Myrtle Beach on October 15, 1954. Sustained winds of 106MPH at landfall, along with a 17-foot storm tide, made Hazel one of the Palmetto State's most destructive hurricanes."

Tidal adjustment: 5.1 ft tide at landfall time. 20-5.1 = 14.9 ft surge

Storm: Connie
Year: 1955
Dates: August 3-15
Max Surge Height: **1.65 m (5.4 ft)** at Fort Macon, NC on 8/1/1955

Source 1: http://www.nhc.noaa.gov/HAW2/english/history.shtml#new
Source 1 Text: Fort Macon, North Carolina reported 75 mph sustained winds with gusts to 100 mph, while a storm surge of up to 8 ft occurred along the coast.
Source 2: North Carolina's Hurricane History by Jay Barnes
Source 2 Text: "Huge waves pounded the coastline, and beach erosion was said to have been worse than that caused by Hazel. tides were about seven feet above normal on the beaches from Southport to Nags Head, and flooding in the sound and near the mouths of rivers were estimated to range from five to eight feet."

Tidal adjustment: 2.6 ft tide at landafall time. 8-2.6 = 5.4 ft surge.

Storm: Diane
Year: 1955
Dates: August 7-21
Max Surge Height: **2.62 m (8.3 ft)** at Long Beach, NC on 9/13/1955

Source 1: North Carolina's Hurricane History by Jay Barnes
Source 1 text: "But as with Connie, Diane's wind drive tides and torrential rains brought extensive flooding to the Tar Heel coast. Tides associated wtih Diane were generally higher than those of the previous hurricane and ranged from five to nine feet above mean low water along the beaches."
Source 2: Wilmington Morning Star
Source 2 text: "Hurricane Diane, swirling 135 MPH winds around its eye, slammed into North Carolina's southerastern coast Tuesday night with torrential rain and tree bending winds that threatened to push tide to 12 feet above normal.....the hurricane's surge of tide was expected to coincide with a full moon high tide." [9/12/55]
"The two front streets of Long Beach were under 4 feet of water." [9/13/55]

USGS topo map puts two front streets of Long Beach at roughly 3 feet above sea level. This yeilds a 7 foot surge, which is roughly equal to what occurred with Connie. Barnes' claim that the tides were generally higher than in Connie, along with his upper limit of 9 feet, causes me to place this surge at 9 ft. Didn't use the 12 foot tide that was potentially there in the earlier report, because it's arrival at high tide means those numbers were likely adjusted to the high side.

Tidal adjustment: 0.7 ft tide at landfall time. 9-0.7 = 8.3 ft surge

Storm: Ione
Year: 1955
Dates: Sept 18-20
Max Surge Height: **3.23 m (10.6 ft)** at New Bern ,NC on 9/19/1955

Source 1:
http://www.csc.noaa.gov/hes/images/pdf/CHARACTERISTICS_STORM_SURGE.pdf
Source 1 text: Figure 23.3 places a 10.6 event at New Bern. Higher event further inland, but this

is the largest tide on open water.

Storm: Flossy
Year 1956
Dates: Sept 23-28
Max Surge Height: **1.34 m (4.4 ft)** at Sewells Point, VA on 9/27/1956

Source 1:
http://www.csc.noaa.gov/hes/images/pdf/CHARACTERISTICS_STORM_SURGE.pdf
Source 1 text: Figure 23.4 places 2 points in Norfolk at 6.6 ft.

Tidal adjustment: 2.2 ft tide at landfall time. 6.6-2.2 = 4.4 ft surge

Storm: Helene
Year: 1958
Dates:
Max Surge Height: **1.31 m (4.3 ft)** at Hatteras, NC on 9/27/1958

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1958.pdf
Source 1 Text: According to Sumner [14], the wind speeds and wind damage associated with Helene indicate a more intense hurricane than Hazel of 1954, but the fact that the center of Helene passed about 20 miles off the coast prevented the extremely high tides and wave damage associated with the 1954 hurricane.
If the storm center had moved inland south of Cape Fear on a northwestward or northward trajectory, the accompanying tides might have exceeded the 16 feet of Hazel. [Note: this source provides a peak surge of 16 feet for Hazel. Other source(s) provide a surge height of 18 feet]
There is also a map in this report listing high tides, with the highest occurring at Hatteras, 7.5 ft
Source 2:
http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1958/helene/prenhc/prenhc28.gif
Source 2 Text: "At 7PM, Hurricane Helene was located…about 45 miles southeast of Cape Hatteras." "Full hurricane conditions are occurring…and tides of 4-7 feet above normal are indicated in this area."
"At Wrightsville Beach, a member of the Weather Bureau staff made a careful swell count on the morning the hurricane arrived. Incredibly, Helene produced only two and a half to three giant swells per minute. This report was described as ' probably the lowest count ever recorded for the area and indicates a storm of exceptional intensity.' Overall, however, tides along the ocean beaches were only three to five feet above normal."
Source 3: http://www.hurricanecity.com/city/wilmington.htm
Source 3 text: Sept 27th hurricane Helene ,130mph from the S.E while turing N.Egusts to 135mph NNE mostly stayed offshore .Heavy damage reported at beach resorts.North winds of 85mph on the 27th at 1:01PM. Rainfall 8.29 inch tides 9ft

Going with 7.5 at Hatteras. The 9 ft number is too high when compared with the 4-7 feet indicated by the wallet. The 7.5 ft value seems like it should be right.

Tidal adjustment: 3.2 ft tide at landfall time.7.5-3.2 = 4.3 ft surge.

Storm: Cindy
Year: 1959
Dates: July 5-12

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1959.pdf
Source 1 text: "The small storm moved northeastward, reaching hurricane intensity a short distance offshore, and the center made landfall about 0245GMT on the 9th between Charleston and Georgetown. Winds of 56kt were recorded at McClellanville, a short distance inland, with squalls estimated at just about hurricane force in the sparsely settled coastal area. The storm tide was about 4 feet above normal."

Storm: Gracie
Year: 1959
Dates: Sept 20-Oct 2
Max Surge Height: **3.05 m (10 ft)** at Jeremy Inlet, SC on 9/16/59

Source 1: http://www.erh.noaa.gov/chs/events/HurrGracie50thAnniv.pdf
Source 1 Text: Gracie struck at low tide, which greatly limited the impact of the storm surge. However, the surge still produced an impressive rise in water. Exact figures vary, but the highest reliable measurement placed the peak water level at 9.7 feet above mean low water on Charleston Harbor early Tuesday afternoon. We now use mean lower low water as the reference for tide levels, and 1959 water levels would be reported a bit higher today. Thus, the tide level peaked close to 10 feet above normal water on Charleston Harbor as Gracie pushed the storm surge into the coast.
Source 2:
http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1959/gracie/prenhc/prelim31.gif
Source 2 Text: The height of the tide in the Charleston area was around 9 ½ ft above mean low water.
Source 3: Encyclopedia of Hurricanes, Typhoones and Cyclones by David Langshore
Source 3 text: "Hurricane Gracie, a moderate Category 3 system that lunged ashore just north of Beaufort on September 16,1959, its 10-foot storm surge and rough seas destroying a number of beachfront buildings but claiming no lives.."..."On September 16,1959, Hurricane Gracie, a moderate Category 3 system, dealt the northern Georgia coast a glancing blow as it trundled ashore just north of Beaufort. A classic coastal hurricane, Gracie's 10 foot storm surge and lurking seas sanded away several Georgian dune ranges but claimed no lives."
Source 3: http://www.hurricanecity.com/city/hiltonheadisland.htm
Source 3 text: Gracie 125mph winds hits the area oct 1st area had gusts to 138mph heavy property & crop damage she spun off 11 tornadoes which killed 12 people in the N.E this was a fast moving storm but still dumped 11 inches of rain barometer 28.05 11 ft s.s hit at 11;00am

Source 4:
http://www.csc.noaa.gov/hes/images/pdf/CHARACTERISTICS_STORM_SURGE.pdf

Source 4 text: Figure 25.3 places an 11.9 ft surge on Edisto Island.

10 feet is mentioned most often, and seems to be tidally corrected. Went with that.

Storm: Donna
Year: 1960
Dates: Aug 29-Sep 14
Max Surge Height: **2.19 m (7.9 ft)** at Atlantic Beach, NC on 9/12/60

Source 1:
http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1960/donna/prenhc/prelim73.gif
Source 1 Text: Tides which were 12 feet above mean low water at 5PM will subside tonight.
Source 2: North Carolina's Hurricane History by Jay Barnes
Source 2 text: " Like so many other great hurricanes, Donna didn't end its journey by fizzling out over the Atlantic. Instead, it maintained its course toward New England and struck Long Island, New York later in the day on September 12. There the storm delivered a ten-foot storm surge and caused extensive damage."

Source 3:
http://www.csc.noaa.gov/hes/images/pdf/CHARACTERISTICS_STORM_SURGE.pdf\
Source 3 text: Figure 26.3 lists surge (less astronomical tide) as 7.9 ft in RI as highest in that region. Also fig. 26.5 lists 10.6 ft at Atlantic Beach, NC, but not sure if that is above MSL or tide. Assuming that it is above MSL, because in 26.3, high water marks are the same as the surge + tide measuremtns, and HWM are presented in 26.5 Will adjust for tides and determine which to go with.

Adjusted Atlantic Beach tide is 7.2 ft, which is lower than the 7.9 in RI. The 12 foot surge claim from the wallet occurred at 5PM. If go with Providence tides, this puts a surge >10 ft, which would trump the other two. However, there is variability amongst tides in this region, and the wallet does not give anything close to a location of these 12 foot tides. Will go with 7.9 ft.

Storm: Cleo
Year: 1964
Dates: Aug 20-Sep 5
Max Surge Height: **1.83 m (6 ft)** at Pompano Beach, FL on 9/27/64

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1964.pdf
Source 1 Text: The tide did not reach 4ft above normal in the Miami area, but was 5ft above normal in Fort Lauderdale and 5-6ft above normal in Pompano Beach.
Source 2: Florida's Hurricane History by Jay Barnes
Sourcd 2 text: "Tides were less than four feet above normal in the Miami area, about five feet at Fort Lauderdale, and five to six feet at Pompano Beach."

Storm: Dora
Year: 1964
Dates: Aug 28-Sep 16
Max Surge Height: **3.66 m (12 feet)** at Anastasia Island, FL on 9/10/64

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1964.pdf
Source 1 Text: Tides estimated at 12 ft swept across Anastasia Island.
Source 2:
http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1964/dora/preloc/gnv1020e.gif
Source 2 Text: St. Augustine – Tides 12 ft, 4 ft higher than any other (tide) known on Anastasia Island.
Source 3: Florida's Hurricane History by Jay Barnes
Source 3 text: "Dora's head-on assault brought a major storm surge to the beaches and low-lying areas in its path. Because of the long duration of Dora's hefty onshore winds, tides five to eight feet above normal flooded the coast of Daytona Beach. Tides estimate at twelve feet - four feet higher than had ever been recorded - swept across Anastasia Island near St Augustine. At Mayport, floodwaters were ten feet above normal."

Storm: Betsy
Year: 1965
Dates: Aug 27-Sep 13
Max Surge: **1.52 m (5.6 ft)** at Miami, FL on 9/8/65

Source 1:
http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1965/betsy/sloshdat/tide1.gif
Note – This is odd that there would be a surge that high so far away from the hurricane.
Source 2: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 2 text: "Storm tides of 6-8 feet and wave action caused considerable flooding between greater Miami and the Palm Beaches."
Source 3: Florida's Hurricane History by Jay Barnes
Source 3 text: "Farther northward at Miami Beach, the storms urge was the greatest since 1926, although it was not even close to the level in that storm. Tides at South Miami Beach measured 6.1 feet above mean low water." "Farther up the coast, high tides, battering waves, and beach erosion were a concern. Tides five to seven feet above normal were reported in Broward and southern Palm Beach Counties, and even the Jacksonville area experienced tides almost two feet above normal....many of Florida's Atlantic coast beaches suffered significant erosion, and seawalls were tested by twelve-foot breakers."
Source 4: http://www.wunderground.com/hurricane/noaareports/at196503.pdf
Source 5: http://www.hurricanecity.com/city/miami.htm
Source 5 text: Betsy sept 8th ,125mph from the east hits key largo,miami gusts over 100mph near 7 ft storm surge.

Tidal adjustment: 1.4 ft tide at landfall time. 7-1.4 = 5.6 ft surge

Storm: Doria
Year: 1967
Dates: Sep 7-19
Max Surge: **1.34 m (4.4 ft)** at Indian River Inlet, DE on 9/15/67

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1967.pdf
Source 1 text: The highest wind reported by a land station near the center was 50 m.p.h. with gusts to 83 m.p.h. at Indian River Inlet, DE. The highest tide, 6.5 ft above normal, also occurred there.

Tidal adjustmetn: 2.1 ft tide at landfall time. 6.5-2.1 = 4.4 ft tide

Storm: Gladys
Year: 1968
Dates: Oct 13-21
Max Surge: **1.52 m (5ft)** at Wilmington, NC on 10/20/68

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1968.pdf
Source 1 text: (Table containing all meteorological data for the storm can be found in the Monthly Weather Review.) Wilmington, NC - 5.0 ft AN on the 20th

Storm: Doria
Year: 1971
Dates: Aug 20-29
Max Surge: **1.25 m (4.1 ft)** at Providence, RI on 8/28/71

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1971.pdf
Source 1 text: (Table containing all meteorological data for the storm can be found in the Monthly Weather Review.)

Tidal adjustment: 1.8 ft tide at landfall time. 5.9-1.8 = 4.1 ft surge/

Storm: Ginger
Year: 1971
Dates: Sep 6-Oct 5
Max Surge: **1.22 m (4 ft)** at Pamlico Sound, NC on 10/1/71

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1971.pdf
Source 1 text: (Table containing all meteorological data for the storm can be found in the Monthly Weather Review.)
Source 2: North Carolina's Hurricane History by Jay Barnes
Source 2: "Tides along the beaches were about four feet above normal, although several locations along the banks of Pamlico Sound recorded tides of five to seven feet.

Couldn't find anything corroborating higher values, so sticking with 4 ft.

Storm: Belle
Year: 1976
Dates: Aug 6-10
Max Surge: **1.37 m (4.5ft)** at Battery Park, Manhattan, NY on 8/10/76

Source 1: http://www.aoml.noaa.gov/general/lib/lib1/nhclib/mwreviews/1976.pdf
Source 1 text: Battery Park at the southern tip of Manhattan had tides of 7.2ft above mean low water, or 4.5 ft above normal. No figures were received from Long Island, where it is suspected that some higher tides may have occurred.
Source 2: New York Times, 8/10/76
Source 2 text: "At one home in Long Island Sound in Mamaroneck, a 35 foot cabin cruiser was lifted over a seawall by high tides and deposited on the grass in the yard."

Storm: David
Year: 1979
Dates: Aug 25-Sept 8
Max Surge: **3.78 m (12.4 ft)** at Tybee Island, GA on 9/4/79

Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1979.pdf
Source 1 Text: Table 4 shows high tide measurements, with almost all measurements marked with an asterisk, denoting tide above normal as being very high in some cases. Very high tides in GA and SC. 12 ft above MSL at Tybee Island, GA, 8.8 ft above MSL at Charleston, SC
Source 2: Florida Hurricanes and Tropical Storms, 1871-2001 by John Willaims
Source 2 text: "It moved inland south of Melbourne on the east coast and then northward along the Indian River Lagoon….severe beach erosion from a storm tide of nearly 5 feet was reported in Brevard County and the southern portion of Volusia County."
Source 3: Florida's Hurricane History by Jay Barnes
Source 3 text: "Large waves pounded the beaches and caused sever eroision in some locations."
Source 4: North Carolina's Hurricane History by Jay Barnes
Source 4 text: "Beach erosion was severe along the southern strands of North Carolina, especially in Brunswick County, where most beaches lost thrity to forty feet of sand. At least a half dozen fishing piers were crippled by the storm. Storm tides were generally three to five feet above normal, although some locations along the banks of Pamlico Sound reported tides of seven feet."

Tidal adjustment: -0.4 ft tide at landfall time. 12-(-0.4) = 12.4 ft surge

Storm: Diane
Year: 1984
Dates: Sept 8-16

Max Surge: **1.68 m (5.5 ft)** at Carolina Beach, NC on 9/14/84
Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1984.pdf
Source 1 Text: Peak surface observations of pressure, wind, tides and rainfall are listed in Table 2. The highest tide height (above normal predicted astronomical tide) or storm surge was 1.7m at Carolina Beach, located slightly north of the point of landfall.
Source 2: North Carolina's Hurricane History by Jay Barnes
Source 2 text: "Fortunately, Diane's stalled movements caused it to weaken, but the timing of its final approach also turned out to be a blessing to beachfront property owners. Landfall occurred very near the time of low tide, and the effects of storm surge were minimal. Beach erosion was somewhat sever from the pounding northeast winds, but the storm tide at Carolina Beach was only five and half feet."

Storm: Gloria
Year: 1985
Dates: Sept 16-Oct 2
Max Surge: **2.1 m (6.9 ft)** at Battery Park, NY on 9/27/1985

Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1985.pdf
Source 1 Text: (Table 5 containing all meteorological data for the storm can be found in the Monthly Weather Review.)
Source 2: North Carolina's Hurricane History by Jay Barnes
Source 2 text: "High tides were most severe along the northern Outer Banks. Highway 12 was overwashed in several locations and sand covered the roadway near Avon and on the northern end of Ocracoke. Tides were generally six to eight feet above normal on the Outer Banks, six feet in the Cherry Point area and four feet at Wrightsville Beach." **good pic on p142**
Source 3: Encyclopedia of Hurricanes, Typhoones and Cyclones by David Langshore
Source 3 text: "The Long Island town of East Massapequa was flooded with 4 feet of water, while skidding 50MPH winds killed two people in New York City"

Source 1 gives a 2.1 m, or 6.9 ft tide at Battery Park, NYC. The vagaries of Source 2's account in both location and amount cause me to go with the NYC tide as the max.

Storm: Charley
Year: 1986
Dates: Aug 13-30
Max Surge: **1.22 m (4 ft)** at Nantucket Island, MA on 8/19/86
Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1986.pdf
Source 1 Text: (Table 3 containing all meteorological data for the storm can be found in the Monthly Weather Review.)

Storm: Hugo
Year: 1989

Dates: Sept 10-25
Max Surge Height: **6.1 m (20 ft)** at Bulls Bay, SC on 9/22/89
Source 1: http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1989-prelim/hugo/prelim08.gif
Source 1 Text: [PG8, Table 2 provides a surge obs of 8.0 feet at Charleston City, SC]
Source 2: http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1989-prelim/hugo/prelim16.gif
Source 2 Text: Few direct tide gage measurements of the storm surge water levels have been received. The tide station in Charleston near the Custom House measured a water level of 12.9 feet above mean lower low water which converts to a storm tide of 10.4 feet above mean sea level or a storm surge of 8.0 feet above the predicted normal astronomical tide height. As far north as Hatteras, North Carolina, the storm surge was reported at 4 feet above the predicted tide. In addition, a considerable number of high water marks gathered by survey teams indicate that the storm tide was 10 to 12 feet above mean sea level at Folly Beach and ranged to near 20 feet at Bulls Bay…13 to 16 feet at McClellanville…13 feet at Myrtle Beach…and to 8 to 10 feet at Holden Beach, North Carolina.
Source 3: http://csc.noaa.gov/hes/docs/postStorm/H_HUGO_ASSESSMENT_REVIEW_UTILIZATION_INFO_DISSEMINATION.pdf
Source 3 Text: [PG 12, Figure 1 depicts a graph of maximum storm tide in feet above N.G.V.D.. The highest value on this graph is approximately 20 feet at Bulls Bay, SC]
Source 4: North Carolina's Hurricane History by Jay Barnes
Source 4 text: "The storm surge on the South Carolina coast wa extreme. The highest tide was near 20 ft at Bull's Bay, just north of Charleston."
Source 5: Encyclopedia of Hurricanes, Typhoones and Cyclones by David Langshore
Source 5 text: "Gusts of up to 100MPH rattled the windows of Savannah, while frothing, 25 foot waves splintered wharves, sank small boats, and breached seawalls."

Storm: Bob
Year: 1991
Dates: Aug 16-29
Max Surge: **2.1 m (7 ft)** at Willets Pt, NY on 8/19/91
Source 1:
http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1991/bob/sloshdat/nwloc01.gif
Source 1 Text: (Table gives tide levels above mean low water, high water and estimated surge. The estimated surge of 7.0 ft exceeds surge values found in the Monthly Weather Review http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1991.pdf, Table 2a, by .1 m)

Source 2: Encyclopedia of hurricanes, typhoons, and cyclones by David Langshore
Source 2 text: "Generated by a central pressure of 28.91 inches (979mb) at landfall near Providence, Bob's 125MPH gusts and 6 foot storm surge caused extensive pier damage along the shores of Narragansett Bay.

Storm: Andrew
Year: 1992
Dates:
Max Surge Height: **5.15 m (16.9 feet)** at Biscayne Bay, FL on 8/24/92
Location of Max Surge Height: Biscayne Bay, FL
Source 1: http://www.nhc.noaa.gov/1992andrew.html

Source 1 Text: During the morning hour of 24 August, Andrew generated storm surge along shorelines of southern Florida (Fig. 7) (103K GIF). On the southeast Florida coast, peak storm surge arrived near the time of high astronomical tide. The height of the storm tide (the sum of the storm surge and astronomical tide, referenced to mean sea level) ranged from 4 to 6 ft in northern Biscayne bay increasing to a maximum value of 16.9 ft at the Burger King International Headquarters, located on the western shoreline in the center of the bay, and decreasing to 4 to 5 ft in southern Biscayne Bay. The observed storm tide values on the Florida southwest coast ranged from 4 to 5 ft near Flamingo to 6 to 7 ft near Goodland ((NOTE: This value is above mean sea level (surge+astrological tide)))

Source 2: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 2 text: from Table 4 on p 97, 16.89 ft
Source 3: Florida's Hurricane History by Jay Barnes
Source 3 text: "But even though news reports focused primarily on the freakish winds, Andrew created a storm surge of record proportions. The surge crested at 16.9 feet, the highest storm tide ever recorded in southeastern Florida. This peak was measured at the edge of Biscayne Bay, very near the Burger King world headquarters."

Storm: Danielle
Year: 1992
Dates: Sep 22-26
Max Surge Height: **1.6m (5.4ft)** at Cape Hatteras, NC on 9/26/92
Source 1:
http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1992/danielle/prenhc/prelim02.gif
Source 1 text: The highest storm surge report was 5.4 feet above normal astrological tide at Cape Hatteras, North Carolina.

Storm: Emily
Year: 1993
Dates:
Max Surge Height: **2.99 m (9.8 ft)** at Buxton, NC on 8/31/93

Source 1:
http://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1993/emily/prenhc/prelim02.gif
Source 1 Text: These strong on-shore winds drove flood waters over the Sound side of Hatteras Island. A storm surge flood height of 10.2 feet above sea level at Buxton is the highest reported value (Table 2).

Source 2:North Carolina's Hurricane History by Jay Barnes
Source 2 text: "Flooding along the shores of Pamlico Sound was about ten and a half feet above normal from just north of Buxton to Avon. AT Frisco and Hatteras village, the tide was about eight and a half feet. Along portions of Highway 12, sound waters came within one vertical foot of breaching the ocean front dunes. Surprisingly, the oceanside surge was moderate, breaking through the dunes in two locations south of Frisco."

Tidal adjustment: 0.4 ft tide at landfall time. 10.2-0.4 = 9.8 ft surge.

Storm: Arthur
Year: 1996
Dates: Jun 17-23
Max Surge: **1.74 m (5.7 ft)** at Cape Lookout, NC on 6/19/96
Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1996.pdf
Source 1 text: Surf as high as 1.5-2.1m occurred off the North Carolina coast in the vicinity of Cape Lookout. No significant erosion was reported.

Tidal adjustment: 1.2 ft tide at landfall time. 6.9-1.2 = 5.7 ft surge.

Storm: Bertha
Year: 1996
Dates: July 5-17
Max Surge: **2.74 m (9 ft)** at Topsail Beach, NC on 7/12/96

Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1996.pdf
Source 1 text: (Table 2 containing all meteorological data for the storm can be found in the Monthly Weather Review.)
NOTE: Higher values (2.4m) are given for storm tide. This value is surge.

Source 2: North Carolina's Hurricane History by Jay Barnes
Source 2 text: ""The highest storm surge, estimated to be between five and eight feet, struck in Pender and Onslow counties and caused extensive structural damages at Topsail Beach, Surf City, North Topsail Beach and Swansboro. The surging tide also overfilled sounds, creeks and inland rivers, destroying hundreds of residential piers and boat docks. Nowhere, however, was the storm's destruction more evident that in the precariously low-lying resort community of North Topsail Beach. Bertha's thirty five mile wide eye moved inland just below Topsail Island, focusing the storm's worst effects on the narrow barrier island. North Topsail Beached, viewed by some as having too little elevation for residential development was haRdest hit. Waves rolled over the area's modest dunes and flooded SR 1568, washing away tons of sand and causing the road to collapse in at least three sections."..."One couple from Ohio barely escaped a confrontation with the tides. After deciding to ride out the storm in their North Topsal home, they apprently changed their minds as the storm reached its peak. They piled into their minivan and attempted the dangerous trek toward higher ground. By that time, however, the water had risen too high, and they were forced to abandon their swamped out vehicle and wade back to

their home through chest deep water."..."In Swansboro, a storm surge of six to eight feet flooded much of the waterfront area."

Source 3: Encyclopedia of hurricanes, typhoons, and cyclones by David Longshore
Source 3 text: At Carolina and Kure beaches some 15 miles south of Wilmington, Bertha's 15 foot breakers buckled fishing piers, smashed storefront windows, tore the roofs and porches from a half dozen houses and rolled a carnival Ferris wheel off its foundation blocks. The southern tip of Topsail Island was inundated by Bertha's nine foot storm surge."

Storm: Edouard
Year: 1996
Dates: Aug 19-Sept 6
Max Surge Height: **1.22 m (4 ft)** at Nantucket, MA on 9/2/96

Source 1: Encyclopedia of hurricanes, typhoons, and cyclones by David Langshore
Source 1 text: "Passing some 80 miles southeast of Nantucket at 12MPH, Edouard's sustained 50MPH winds, 80MPH gusts and 4 foot seas flooded waterfront streets with more than 12 inches of water.

When adjusting for tide, tides are greater than 4 ft (struck at high tide). I feel as though this value must be above that high tide, because otherwise Langshore would simply be describing normal high tide, and there would not be flooded streets. Will hold value at 4ft.

Storm: Fran
Year: 1996
Dates: Aug 23-Sept 10
Max Surge Height: **3.66 m (12 feet)** at Figure Eight Island, NC on 9/6/1996

Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1996.pdf
Source 1 Text: (Table 6 containing all meteorological data for the storm can be found in the Monthly Weather Review.)
Source 2: http://www.nhc.noaa.gov/1996fran.html

Source 2 Text: At the time of this report, a post-storm high water mark survey was being conducted by the U.S. Army Corps of Engineers and the U.S. Geological Survey. Many high water marks remain to be surveyed and "tied into" bench marks. The locations of the maximum values cannot be finalized until the survey is complete. However, initial survey results show an extensive storm surge along the North Carolina coast primarily southwest of Cape Lookout. Still water mark elevations on the inside of buildings, indicative of the storm surge, range from 8 to 12 feet. Outside water marks on buildings or debris lines are higher due to the effect of breaking waves.

Source3: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 3 text: from Table 4 on p 98, 4-6 ft in FL
Source 4: "North Carolina's Hurricane History by Jay Barnes

Source 4 text: "According to NWS reports, the heavy storm surge that affected much of North Carolina's southeast coast ranged from eight to twelve feet. Still water marks measured inside buildings provided these elevations; exterior water levels were generally higher due to wave action......preliminary reports from the WS indicated that Fran's surge was ten feet at Swansboro and New Bern, nine at Washington and Bellhaven and seven at Atlantic Beach."

12 feet looks good, especially based on the fact that exterior heights were greater than the still of 10 feet measured.

Storm: Bonnie
Year: 1998
Dates: Aug 19-31
Max Surge Height: **1.83 m (6.0ft)** at Coastal Pasquotank, NC on 8/28/1998

Source 1: http://www.nhc.noaa.gov/1998bonnie.html
Source 1 Text: (Table 2 containing all meteorological data for the storm can be found in the Monthly Weather Review.)
NOTE – Storm tides much higher
Storm tides of 5 to 8 feet above normal were reported mainly in eastern beaches of Brunswick County NC, while a storm surge of 6 feet was reported at Pasquotank and Camdem counties in the Albemarle Sound.

Storm: Dennis
Year: 1999
Dates: Aug 24-Sept 8
Max Surge Height: **2.41 m (7.9 ft)** at Oriental, NC on 8/30/99
Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1999.pdf
Source 1 text: Few detailed observations of storm surge are available from areas affected by Dennis. Storm tides up to 1.5 m above normal were reported along much of the North Carolina coast on both 30 August and 4 September. Areas along the Neuse River reported tides 3 m above normal tide level on 30 August, while areas along the Pamlico River reported similar heights on 4 September. Portions of the South Carolina and southeastern Virginia coasts experienced tides about 1 m above normal.

Source 2: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 2 text: from Table 4 on p 99, 6 ft. , but no location given.

Storm: Floyd
Year: 1999
Dates: Sept 7-19
Max Surge Height: **2.04 m (6.7 ft)** at Oak Island, NC on 9/17/1999

Source 1: http://www.nhc.noaa.gov/1999floyd.html

Source 1 Text: Storm surge values as high as 9 to 10 feet were reported along the North Carolina coast. (NOTE: Listed as tides in Table 6. Also, Boston, MA has a higher tide reading.)
Source 2: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/1999.pdf
Source 2 Text: (Table 4 containing all meteorological data for the storm can be found in the Monthly Weather Review.)
Source 3: Florida Hurricanes and Tropical Storms, 1871-2001 by John Williams
Source 3 text: From Table 4 on p 99, up to 10
Source 4: Winston Salem Journal, 9/17/99, p A12
Source 4 text: "The Island [Oak Island] had storm surges of 15 feet. Waves broke through the glass garage doors of A Whale of a Time, a restaurant and entertainment center on Yaupon Beach." There is also a photograph of the road overwashed from the surge at this location.
Source 5: http://www.hurricanecity.com/city/wilmington.htm
Source 5 text: sept 16th Hurricane Floyd hit just east with 110mph winds from the south,dumps nearly 20 inches of rain here & causes heavy damage to north on oak island.New Hanover county reported 10 ft storm surge on sound side of Masonboro.A record 13.38 invhes fell in 24 hrs.

AOML has Oak Island at 3.1 m, Boston at 3.3 m
Going with 10ft surge at Oak Island. Whale of a Time restaurant is 10 ft above sea level.

Tidal adjustment: 3.3 ft surge at landfall time. 10-3.3 = 6.7 ft surge.

Storm: Gustav
Year: 2002
Dates: Sept 8-15
Max Surge Height: **1.68 m (5.5 ft)** at Dare, NC on 9/11/02
Source 1: http://www.nhc.noaa.gov/2002gustav.shtml
Source 1 text: Storm surge flooding of 5-6 ft above normal tide levels occurred along the inland side of the Outer Banks in Hyde and Dare counties. This occurred during a period of strong northwesterly winds following the passage of the center of Gustav.

Storm: Isabel
Year: 2003
Dates: Sept 6-20
Max Surge Height: **3.28 m (10.75 ft)** at Smithfield, VA on 9/18/03
Source 1: http://www.nhc.noaa.gov/2003isabel.shtml
Source 1 text: (Table 3 containing all meteorological data for the storm can be found in the link.)

Storm: Charley
Year: 2004
Dates: Aug 9-15
Max Surge Height: **2.29 m (7.5 ft)** at Long Beach, NC on 9/14/2004
Source 1: http://www.nhc.noaa.gov/2004charley.shtml

Source 1 text: (Table 5 containing all meteorological data for the storm can be found in the link.)

Storm: Gaston
Year: 2004
Dates: Aug 27-Sep 3
Max Surge Height: **1.37m (4.5 ft)** at Bulls Bay, SC on 9/29/04
Source 1: http://www.nhc.noaa.gov/2004gaston.shtml
Source 1 text: (Table 3 containing all meteorological data for the storm can be found in the link.)

Storm: Frances
Year: 2004
Dates: Aug 25-Sep 10
Max Surge Height: **2.44 m (8 ft)** at Vero Beach, FL on 9/5/2004

Source 1: http://www.nhc.noaa.gov/2004frances.shtml
Source 1 text: (Table 3 containing all meteorological data for the storm can be found in the link.)\
Source 2: Florida's Hurricane History by Jay Barnes
Source 2 text: "Frances produced moderate storm surges along Florida's Atlantic and gulf coasts. The National Weather Service office in Melbourne estimated that storm surges reached eight feet near Vero Beach and six feet at Cocoa Beach. Tides were as much as two feet above normal as far north as the Georgia coast."
Source 3: http://www.hurricanecity.com/city/vero.htm
Source 3 text: Sept 5th, Hurricane Frances hits with 105mph winds from the ESE . Many trees down,signs damaged power out for days a very large & slow moving hurricane,3 to 4 mobile homes unroofed,numerous trees down.Wooden boardwalk on beach nowhere to be found. 1 death in Indian river county.approx 8 ft storm surge

NHC link also mentions the estimated surge of 8 feet. This combined with other accounts confirm 8 ft surge.

Storm: Jeanne
Year: 2004
Dates: Sep 13-29
Max Surge Height: **1.83 m (6 ft)** at Melbourne, FL on 9/26/04

Source 1: http://www.nhc.noaa.gov/2004jeanne.shtml
Source 1 Text: A storm surge of 3.8 ft above normal astronomical tide levels was measured at Trident Pier at Port Canaveral, Florida about an hour after landfall. Storm surge flooding of up to 6 ft above normal tides likely occurred along the Florida east coast from the vicinity of Melbourne southward to Ft. Pierce. On the Florida west coast, a negative storm surge of about 4.5 ft below normal tides was measured at Cedar Key when winds were blowing offshore. This

was followed by a positive surge of about 3.5 ft above normal when winds became onshore.\
Source 2: Florida's Hurricane History by Jay Barnes
Source 2 text: "Storm surge flooding along the ocean beaches just north of landfall was likely 6 feet above normal. Interestingly, along Florida's Gulf coast on Cedar Key, offshore winds generate by Jeanne's passing created a negative surge of 4.5 feet, meaning that the water receded by this amount during the storm's approach. After Jeanne passed and the winds shifted, a positive surge of about 3.5 feet above normal was recorded on these Gulf beaches."

Storm: Ophelia
Year: 2005
Dates: Sep 6-23
Max Surge Height: **1.52 m (5 ft)** at Onslow Beach, NC on 9/15/2005

Source 1: http://www.aoml.noaa.gov/hrd/hurdat/mwr_pdf/2005.pdf
Source 1 text: (Table 8 containing all meteorological data for the storm can be found in the Monthly Weather Review.)
ALSO: Ophelia caused storm surges of 4 to 6 ft above normal tide levels in the Pamlico Sound including the lower reaches of the Neuse, Pamlico, and Newport Rivers. Surges of 4 to 6 ft also occurred along the open coasts in Onslow and Cartaret counties. Storm surges of 3 to 4 ft above normal tide levels were common elsewhere along the affected areas of the North Carolina coast. Ophelia also caused tides of 1 to 2 ft above normal along the Florida coast

Placed surge at Onslow Beach, NC, andsplit 4 to 6 ft estimate to 5 ft.

Storm: Hanna
Year: 2008
Dates: Aug 28-Sep 8
Max Surge Height: **1.52 m (5 ft)** at Wilmington, NC on 9/8/08
Source 1: http://www.nhc.noaa.gov/pdf/TCR-AL082008_Hanna.pdf
Source 1 text: (Table 3 containing all meteorological data for the storm can be found in the link.)

Storm: Earl
Year: 2010
Dates: Aug 28-Sep 8
Source 1: http://www.nhc.noaa.gov/pdf/TCR-AL072010_Earl.pdf
Source 1 text: The highest storm surge value reported was 4.27 ft at Hatteras Village, North Carolina.
Earl produced a surge of up to 3 ft across a large portion of the U.S. coast from North Carolina to Maine. Storm tide values around 19 ft were reported in Maine, but these were dominated by tidal effects.

Storm: Irene
Year: 2011
Date: 8/28/2011
Max Surge Height: **2.16 m(7.1 ft)** at Long Beach, NY on 8/28/2011

Source 1: http://wim.usgs.gov/stormtidemapper/stormtidemapper.html#
Source 1 text: Interactive website lists tidal readings and gauge heights from Irene. Long Beach is the site with the highest tide above NDGV through both methods. Tidal influences may play a role.
Storm tide mapper tool places a 9.8 ft surge at Long Beach, NY at noon on the 28th. Highest can find using that tool

Source 2: http://www.hurricanecity.com/city/capehatteras.htm
Source 2 text: The hurricane forced waters up into the Currituck and Albemarle sounds and when winds shifted, the pent-up waters came rushing back toward the south.Post storm surveys indicate a surge of 8 to 11 ft occured in portions of Pamlico Sound. There was widespread flooding of buildings on both sides of Roanoke Island including Wanchese and Manteo. Many homes flooded on the soundside of the beach towns and in Dare County's unincorporated areas including East Lake, Stumpy Point, Colington Harbor and Manns Harbor, all of which report major damage.Official high wind gust at uscg station 79mph sustained 60mph

Long Island vs Cape Hatteras. LI was likely more influenced by tide, and the number is smaller to begin with. However, WIM database does not validate the 8-11 foot surge, although high water marks can not be viewed for some reason. Need more.

Tidal adjustment: 2.7 ft tide at landfall time. 9.8-2.7 = 7.1 ft surge.

APPENDIX 2: CODE USED TO GENERATE K-MEANS CLUSTER ANALYSIS IN R COMPUTER PROGRAMMING LANGUAGE

```
#Load the necessary libraries
library (maps)
library (RColorBrewer)

#Create variable named statelist and list the states to map
statelist=c("Florida","Georgia","Alabama","South Carolina","North Carolina")

#Draw map of the region
#Open table with surge data
file=read.table('F:/R_datafile1.csv',header=1,sep=',')
#Pull out lat and lon values
lat=file$Lat
lon=file$Long

png('F:/atlanticreturn.png',width=800,height=800,unit='px')
map('state',region=statelist,xlim=c(-89,-73),ylim=c(23,37))
points(lon,lat,col='yellow',pch=20,cex=3)

num_runs=1000

run_kmeans = function(i) {
  output=kmeans(data.frame(x=lon,y=lat),centers=6)
 return(output)
    }

output_runs = sapply(1:num_runs,run_kmeans)

get_size = function(i) { return(output_runs[,i]$size) }

size_list=sapply(1:num_runs,get_size)

get_min_size = function(i) {return(min(size_list[,i]))}

indx = which.max(sapply(1:num_runs,get_min_size))

print(indx)

print(output_runs[,indx])


#output=kmeans(data.frame(x=lon,y=lat),centers=10)
#cl_centers = output$centers

col_pal = brewer.pal(10,'Spectral')
```

```
points(lon,lat,col=col_pal[output_runs[,indx]$cluster],pch=20,cex=3)

points(output_runs[,indx]$centers,col='black',pch=20,cex=3)

#Provide a title for the map
title(main="South Atlantic Coast Clusters",cex.main=2)

fileb=cbind(file,output_runs[,indx]$cluster)
write.table(fileb,'F:/R_datafile1.csv',sep=',',row.names=F,col.names=F)

#close output device
dev.off()
```

VITA

Stephen Beckage was born on June 24 to Richard and Catherine Beckage in Scranton, Pennsylvania. He was raised in Dunmore, Pennsylvania, and graduated from Dunmore High School in June 2006. He attended the Pennsylvania State University, where he majored in Geography with a minor in Climatology. He received his Bachelor of Science degree in May 2010. He is expected to receive his Master of Science degree in Geography and Anthropology from Louisiana State University in August 2012. He expects to move to New York City upon graduation.