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# INTERCATEGORY AND INTERBASIN COMPARISON OF STORM SURGE HEIGHT

By

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# INTERCATEGORY AND INTERBASIN COMPARISON OF STORM SURGE HEIGHT

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Hurricanes strike the coast along the Gulf of Mexico and eastern Seaboard of the United States annually. With each hurricane that makes landfall there is potential for significant damage and destruction with the majority of coastal devastation occurring from storm surge. It is accepted that hurricane strength, classified by the Saffir-Simpson scale, and storm surge height are directly proportional. However, this scale may prove to be a false representation of the height of storm surge, especially according to location of landfall. This study will discuss the correlation between category 2, and greater, hurricanes and corresponding storm surge heights between the Gulf Coast and Atlantic Coast. Through this research it shows that there is a variation in storm surge height between regions, concluding that the Gulf Coast is prone to higher surge heights than the Atlantic for like-category storms.

# DEDICATION

I would like to dedicate this research to my family and friends and their continued support and encouragement. I could not have done it without you. Thank you!

# ACKNOWLEDGEMENTS

The author would like to express sincere gratitude to committee members, Dr. Grady Dixon, Dr. Michael Brown, and Dr. Charles Wax, for assistance with completion of this study. Personal thanks to Dr. Grady Dixon for continued guidance and assistance.

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# INTRODUCTION

Hurricanes strike the coast along the Gulf of Mexico and Eastern Seaboard of the United States many times annually. With each hurricane that makes landfall, there is potential for significant damage and destruction, especially through rapidly-growing coastal regions where damage could be exacerbated by population density (Pielke and Landsea 1998). Most coastal devastation from a hurricane is caused by storm surge (Hoover 1957) and it is generally accepted that hurricane strength and storm surge height are directly proportional (Coch 1994). Whereas, a hurricane's strength is classified by the Saffir-Simpson Hurricane Scale; the Saffir-Simpson scale divides hurricanes into five categories based upon wind speed, with category 1 being the weakest and category 5 being the strongest (Saffir 1977; Simpson and Riehl 1981). However, this scale imperfectly correlates with the height of a storm surge, which can consequently lead to underestimated projections of potential damage to an area. See Table 1.1 for the Saffir-Simpson scale wind speed to predicted storm surge.

Table 1.1 Saffir-Simpson Hurricane Scale

| **Category** | **Wind Speed (mph)** | **Storm Surge (ft)** |
|---|---|---|
| 1 | 74-95 | 4-5 |
| 2 | 96-110 | 6-8 |
| 3 | 111-130 | 9-12 |
| 4 | 131-155 | 13-18 |
| 5 | ≥155 | ≥18 |

Although some of the costliest hurricanes have been category 4 or greater, this does not denote that storms of lesser strength should be considered less destructive. For example, Hurricane Katrina (2005) was a category 3 hurricane at landfall, yet, it was the costliest hurricane recorded in the United States, at an estimated $200 billion (Knabb et al. 2006). When predicting damage potential associated with storm surge, the Saffir-Simpson scale can be misleading, thus specific variables that enhance or contribute to storm surge height should become the most important factors under review. Therefore, the scientific scale on how to best describe the destructive potential of hurricanes must be reevaluated and altered. Powell and Reinhold state that factors like bathymetry, surface roughness, storm motion, and coastline shape should be individually considered, and further studied, as variables in a scale used for destructive potential.

This study seeks to identify one of these factors, coastal geography, as a primary variable to be considered when determining potential damage caused by resulting storm surge. Storm surge heights will be compared between the Atlantic Coast region and the Gulf Coast Region for like-category storms ranging from category 2 to category 5. In addition, the variability of storm surge heights between category 2 and category 5 storms will be determined for each region. The possibility of elevated water levels in the Gulf of

Mexico region due to wave propagation from tropical cyclones has been noted (Cline 1920). This assertion was made nearly 90 years ago and the idea must be re-visited in order to start assessing the validity of the Saffir-Simpson scale as a proper tool of measure for potential storm damage.

The objective of this study is to show the relationship between coastal geography and storm surge height by studying category 2, 3, 4 and 5 hurricanes, based on the Saffir-Simpson hurricane scale. This study will exclude category 1 storms because of their relatively low surge heights and minimal damage.

According to Bush (2001), the Saffir-Simpson hurricane scale reflects the strength of a hurricane over the ocean; however, the scale is less adequate in reflecting the effects of a hurricane on the coast at landfall. It is anticipated that this research will help to identify regions prone to higher storm surge in order to provide better projections of potential damage to an area and to lead to better-informed and more quickly evaluated evacuation orders and evacuation deliberations.

The hypothesis for this study is that the Gulf Coast Region is the most vulnerable, and prone to higher storm surge heights, due to the coastal geography of this region. The concave coast of the Gulf of Mexico acts to trap and push water inland by converging it, and the gradual incline of the shallow ocean floor does nothing to hinder wave energy. Conversely, the Atlantic Coast is less likely to encounter extreme storm surge heights because the ocean water can be dissipated back into the open seas and the shelf-like bathymetry reduces the momentum and energy of ocean waves

Ultimately, it will be determined if storm surge heights produced by like-category storms vary between the Atlantic Region and the Gulf Coast Regions for all Category 2, 3, 4, and 5 hurricanes from 1969—2005. Also, the variation in storm surge heights between categories for each region will be noted.

# CHAPTER II

# LITERATURE REVIEW

A storm surge generated by a hurricane is known to be the most destructive part of the storm (Hoover 1957), yet more research must be conducted to gain a better understanding of which variables are most important in determining storm surge height. The following literature review defines variables necessary for hurricane development and intensification, variables contributing to storm surge height, modeling tools used to determine surge height, population, which increases costs associated with storm surge, and brief storm summaries for storms used in this study.

## Hurricane Development and Intensification

### *Warm Sea Surface Temperatures*

It is generally accepted that sea surface temperature (SST) is an important environmental variable to consider when studying hurricane development and intensification. In fact, storm intensity has been shown to vary directly with the mean SST (Landsea 1993). Additionally, DeMaria and Kaplan (1994) made a direct correlation between SST and hurricane wind speeds as a factor contributing to the intensification of a hurricane. Palmén (1948) proposed that vertical instability, in the atmosphere above the Atlantic Ocean, was a necessary condition for the formation of hurricanes and concluded that hurricanes only form in regions where the SST is greater than 26° C. Moreover, Korolev et al. (1990) and Pudov (1992) observed that the contrast between the sea temperature and air temperature (sea-air temperature), for two tropical storms, increased from 1°C to 6°C as surface wind speed increased from 12 to 25 $ms^{-1}$. Korolev et al. (1990) and Pudov (1992) suggest that, not only SST, but also the relationship between the sea-air temperatures plays a role on the surface wind speed. Carlson (1971) shows that seasonal hurricane activity is correlated with varying sea surface temperatures.

### *Weak Vertical Wind Shear*

Weak vertical wind shear is a favorable environmental factor for hurricane development (Gray 1968) since weak vertical wind shear allows for a stronger core of the hurricane (Frank and Ritchie 1999). Wind shear values of less than 10 $ms^{-1}$ favor intensification, whereas shear values greater than 10 $ms^{-1}$ are associated with weakening (Paterson et al. 2005). A highly sheared environment tends to disrupt the structure of a hurricane's eyewall, whereas more uniform winds allow a hurricane to grow to maximum potential (Nash et al. 2003).

### *Placement of Subtropical Anticyclone*

The subtropical anticyclone, or Bermuda High, is a semi-permanent feature in the Atlantic Ocean and is responsible for the general circulation of the atmosphere (Asnani 2005). Subtropical anticyclones tend to move north-south and east-west with seasonal changes. Although there is a two to three week lag time involved, subtropical anticyclones move south beginning in early July, just following the summer solstice

(Asnani 2005). The subtropical high promotes hurricane intensification by effectively lessening the vertical wind shear. Thus, it is reasonable to suggest that hurricane intensification and direction are strongly influenced by the placement of the subtropical anticyclone’s southward.

## Storm Surge

SST, vertical wind shear, and placement of the subtropical high are the primary influences for tropical cyclone development and intensification, however, storm surge generation is influenced by several other factors. The physical and environmental variables that contribute to the formation and propagation of storm surge are wind speed, central pressure, shelf slope, shoreline configuration, and human effects on shorelines (Coch 1994). Although storm surge is a result of several environmental variables, studies suggest that the most important variable contributing to storm surge height is pressure and, subsequently, wind. While storm surge is a function of pressure, the maximum surge does not occur under or near the eye of the hurricane where pressure is lowest. Instead, maximum storm surge heights occur in the right, front quadrant of the hurricane where the wind speed is the greatest (Coch 1994). Strong onshore winds cause water to build up along the coast, and when this occurs in conjunction with a naturally occurring high tide, coastal defenses can be breached (Amedo 2005). Storm surge is a good measure of a hurricane's energy flux at the shoreline as opposed to a hurricane’s overall strength or intensity, based on the Saffir-Simpson hurricane scale (Bush 2001). Therefore, it is important to investigate coastal features, which can enhance storm surge height, and not rely solely on the Saffir-Simpson hurricane scale as an indicator for coastal destruction.

## Models

Due to the lack of measured or true storm surge data availability, computer models are currently used to model storm surge heights. Models are an important tool for scientists and engineers, however, models are not easily accessible, or understood by the public. The public can better relate to and recognize categorical divisions of storms. Inherently, models are not the most favorable form of data or the most accurate. Although the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model is the most notable and widely used, other models such as the Advanced Circulation (ADCIRC) and High Resolution Surge Model (HRSM) are also utilized to determine storm surge. The following section will briefly describe these models, benefits, and constraints of each.

The oldest and most widely used model for storm surge data is the SLOSH Model. Although the SLOSH Model has been tested extensively and commonly used, the resolution is limited. Also, the SLOSH Model is not the most ideal tool to determine storm surge due to limited input about the storm intensity and structure, and SLOSH has difficulty simulating convoluted shorelines (Houston et al. 1999). Such features include barrier islands, similar to those located across much of the Central Gulf Coast Region, or large bays, such as Mobile Bay in Mobile, Alabama. In addition, it is difficult for the SLOSH Model to incorporate features that block or accelerate storm surge flooding and neglects to incorporate astronomical tides (Zhang et al. 2008).

Despite the recent development of the ADCIRC, it is capable of producing more accurate model output than SLOSH. This is due to the fact that the ADCIRC Model domain is extremely flexible and its resolution is much finer than the SLOSH Model. Furthermore, the ADCIRC model simulates convoluted shorelines reasonably well and it can also incorporate features such as small as highways and canals that can affect the acceleration of a storm surge (Luettich and Westerink 2004). The output for a numerical model like ADCIRC is dependent on reliable wind and pressure field inputs along with proper bathymetric and land elevation models (Demirbilek et al. 2008).

Lastly, much like the ADCIRC model, the HRSM model is not as widely used and is a recent technological advancement designed to improve storm surge modeling. Like the ADCIRC, the HRSM can simulate convoluted shorelines and take into account physical coastal features. Unfortunately, model output is not widely available and is not easily accessible.

## Coastal Population Growth

It is important to note coastal population growth because, as suggested by Pielke and Landsea (1998), the increasing coastal population only exacerbates the potential for damage caused by hurricanes. According to the United States Census Bureau, coastal population increased by 23.6 million between 1980 and 2005; in 2003, an estimated 153 million people (nearly 53 percent of the population) lived in coastal counties (Crossett et al. 2004). This increasing coastal population density coupled with the fast-growing economy of coastal areas increases the risks and dangers associated with hurricanes and storm surge. If this trend continues, its economical impacts will pose immense challenges for coastal communities when threatened by natural disasters such as hurricanes (Perkins 2004).

## Hurricane Summaries

The following summaries include all hurricanes that made landfall as a category 2 storm or greater in the United States from 1969—2005 and storms with inadequate surge data for this project were discarded.

### *Camille 1969* (Simpson et al 1970)

Hurricane Camille started as a tropical wave off the coast of Africa on 5 August 1969, during a time when flow patterns at the mid-latitudes were more zonal and the subtropical high was more persistent. This combination, noted by Simpson and Sugg, 1969, of the National Hurricane Center, appeared to control the intensity of tropical cyclones during the 1969 season rather than the formation.

On 9 August, cloudiness associated with the disturbance began to take on circular form. The storm remained without a defined center of closed circulation until 14 August, where reconnaissance aircraft reported a central pressure of 991 mb. On 15 August, as the storm reached the western tip of Cuba, the central pressure dropped to 964 mb with winds near 52 $ms^{-1}$. Officially a hurricane, Hurricane Camille rapidly intensified over the next 48 hours with the central pressure dropping to 905 mb by early evening 16 August. Substantial inflow and assistance of a high-speed, northward-moving current contributed to the rapid intensification and maintenance of Camille's strong mass circulation.

Trends indicated landfall somewhere near Panama City, Florida, and warnings were issued for most of the Florida panhandle. Hurricane Camille barreled toward

Clermont Harbor, Waveland, and Bay St. Louis, Mississippi near midnight 17 August, much farther west than previously forecasted. As of 1969, Hurricane Camille had the highest recorded wind speed, central pressure, and storm surge.

With a central pressure of 905 mb, winds in excess of 90 $ms^{-1}$ at landfall, and storm surge heights over 7.32 meters, it is not a wonder that over $1 billion worth of damages occurred from this storm. Luckily, there was less loss of life per million dollars of damage than any other Atlantic storm.

*Celia 1970* (Simpson and Pelissier 1971)

A small, typical, late July wave moved off the African coast and six days later became a depression of the Caribbean Islands. Here the light wind shear allowed this small area of convection to start growing and a well defined eye was reported on 31 July. Depression status was maintained as it moved toward the northern tip of Cuba. Once the depression emerged into the Gulf of Mexico, rapid intensification occurred. It was noted that the development was eerily similar to Hurricane Camille. After interaction with the Yucatan Peninsula, weakening occurred. Although most indicators suggested that Celia would maintain her status until landfall a second reintensification occurred just 8 hours prior to landfall.

Celia made landfall near Corpus Christi, Texas with the highest storm surge values of 2.80 m recorded at Aransas Port and Rockport. Sustained winds were between 31 and 36 $ms^{-1}$. Although Celia was a category 3 storm at landfall, it was classified as one of the costliest storms at over $444 million.

*Edith 1971* (Simpson and Hope 1972)

The only major hurricane of 1971, Edith, started as a cluster of clouds that formed within the Intertropical Convergence Zone (ITCZ) on 2 September. Over the next few days it appeared that the storm diminished due to the cloud cover in the ITCZ. After moving out of the ITCZ it was clear that a well defined area of a circulation existed and a tropical depression had formed. By 7 September Edith became a category 1 hurricane. As it moved westward towards the country of Honduras there was little change in the strength and direction. Suddenly though on 9 September, just hours before making landfall on Cape Gracias, it quickly intensified from a minimal hurricane to a category 5 storm and there were environmental elements present when Edith strengthened, similar to Camille (1969) and Celia (1970). It is suggested that a release of energy at the upper-level is responsible for the rapid strengthening of these storms. After remaining over land for multiple days, Edith lost its hurricane status.

Edith, yet again a tropical storm, drifts northward toward the Yucatan peninsula. After passing the Yucatan peninsula, Edith reintensifies in the open waters of the Gulf of Mexico and became a hurricane yet again. With a northeasterly track, Edith made landfall about 46 km east of Carmen, Louisiana.

At landfall, the highest sustained winds were recorded at 31 $ms^{-1}$, gusting to 43 $ms^{-1}$. Storm surge values were reported up to 2.45 m. Total damage was estimated at $25 million.

*Carmen 1974* (Hope 1975)

Hurricane Carmen started as an easterly wave, which moved off the African coast on 23 August 1974 and became a depression on 29 August. During its westward track south of Puerto Rico Carmen strengthened, however, intensification was not rapid due to the lack of low-level inflow whilst over Hispaniola and eastern Cuba. Mean sea-surface temperatures were actually below normal but were above the developmental threshold value of 27˚C, set by Palmén (1948).

Carmen approached the Yucatan Peninsula on 2 September and began to rapidly develop due to warm Caribbean Sea temperatures coupled with favorable outflow aloft. Pressure readings fell to 928 mb with wind speeds near 67 $ms^{-1}$ just before impacting Belize. Carmen weakened after passing over Belize but soon regained strength when it moved over the warm waters of the Gulf of Mexico on 5 September.

Hurricane Carmen made landfall on the Louisiana coast on 8 September and quickly weakened due to cool, dry air being added to the system from a low pressure system near Texas. Carmen affected the sugar cane industry due to flooding rains, impacted the shrimp industry, and cost the off shore oil installations millions of dollars. Total damages were estimated near $150 million.

*Eloise 1975* (Hebert 1976)

A visibly unimpressive disturbance developed off the African coast on 6 September, although soundings indicated a stronger lower-level cyclonic rotation. Before being named a depression on 10 September, this system moved across the Atlantic at 13 knots with an increase in organization, based upon ship records and satellite images.

Despite the next six days, where wind direction fluctuation aloft inhibited significant intensification, Eloise was named a tropical storm on 16 September. After trekking across Hispaniola and Cuba, and weakening to minimal tropical storm strength, Eloise did begin to gain strength and intensity as it neared the Yucatan peninsula on 20 September. A deep upper-level trough enhanced outflow aloft and hurricane status was given to Eloise by morning on 22 September.

Hurricane Eloise strengthened over the warm Gulf of Mexico waters and made landfall between Fort Walton Beach and Panama City, Florida at 1200 UTC. At landfall, Eloise had a minimum central pressure of 955 mb with sustained winds at 57 $ms^{-1}$, gusting up to 70 $ms^{-1}$. The diameter of the eye of the storm was 44.45 km and maximum storm surge values ranged between 3.66—4.88 m on the Florida coast.

*Frederic 1979* (Hebert 1980)

A benign wave left the cost of Africa on 27 August 1979. The wave quickly began rotating by 29 August and a tropical depression was formed. Thirty hours later tropical storm Frederic was named. Continuing directly westward at 9.3—10.3 $ms^{-1}$, Frederic had been upgraded to a hurricane by 1 September. Despite rapid development during the early stages of this system, the lingering atmospheric outflow from hurricane David impeded further intensification as Frederic neared Hispaniola. Also, as Frederic encountered island after island, the system slowed, lower level circulation was disrupted, and Frederic was reduced to depression stage again. Frederic maintained its westward direction and, as it moved south of Cuba, was uninhibited in the open waters. At this point, Frederic began to strengthen, and on 7 September, regained tropical storm status.

Turning slightly to the northwest, Frederic encountered a very warm SST, between 29—30°C, and established strong anticyclonic rotation in the upper levels, thus, Frederic became a hurricane again on 10 September. Continuing a more northward track, Frederic made landfall on Dauphin Island, Alabama on 13 September at 0300 UTC.

Upon landfall, records show a central pressure of 946 mb and winds estimated at 59 $ms^{-1}$. Maximum storm surge heights were 2.44—3.66 m from Pascagoula, Mississippi, to western Santa Rosa Island; within Mobile Bay, maximum storm surges ranged from 2.13 m on the east side to 3.96 m along the middle to western shore. Frederic caused over $2 billion in damages, spawned a number of tornadoes, and caused the evacuation of nearly 250, 000 persons.

*Allen 1980* (Lawrence and Pelissier 1981)

Hurricane Allen started as a typical wave off the African coast, one unique characteristic of this storm was the fluctuation in intensity during its lifetime (Figure 2.1). From storm genesis until landfall, Allen managed to maintain steady movement and keep the storm center over water. Allen moved at a speed ranging between 9.3—11.3 $ms^{-1}$. When Allen was centered over Cuba, it began to slow in speed. The slowing was associated with a strong low pressure off the southeastern United States. As Allen moved through the Yucatan channel, pressure reading fell to 899 mb. The pressure rose to 916 mb as the storm moved into the Gulf of Mexico. Upon landfall, Allen had a central pressure of 945 mb and wind speeds of 51 $ms^{1}$. Winds gusted up to 54 $ms^{-1}$ in Port Mansfield where there was also a storm surge of 3.66 m.

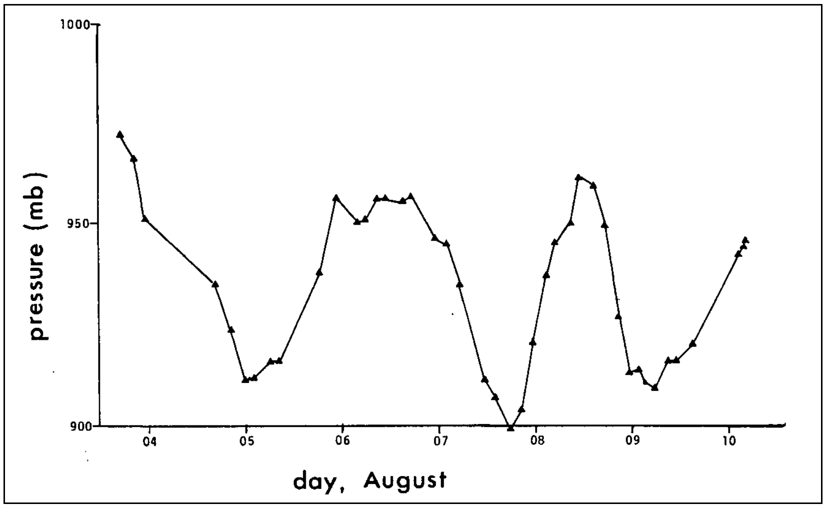

Figure 2.1 Hurricane Allen; Pressure vs. Time

*Alicia 1983* (Case and Gerrish 1984)

An area of low pressure moved off the Mississippi and Alabama coasts on 14 August 1983 and primed the atmosphere over the Gulf of Mexico for what was soon to be Hurricane Alicia. With high environmental pressures surrounding the developing system, the storm remained rather small in size. Hurricane Alicia was a slow-moving storm that made landfall 40 km southwest of Galveston, Texas. Wind speeds were above 42 ms$^{-1}$ with a pressure at landfall of 962 mb. Resulting storm surges ranged between 0.6—4 m form Corpus Christi, Texas to San Luis Pass, Louisiana.

*Diana 1984* (Lawrence et al. 1985)

Diana began as a developing low pressure system north of the Bahamas during early September 1984. After wind reports of 18 ms$^{-1}$, on 8 September, the storm was named. Within the next 24 hours, Diana intensified to hurricane strength and started moving to the north-northwest, parallel to the Georgia/South Carolina coast. Figure 2.2 and Figure 2.3 show the progression of Diana as it followed the coastline.

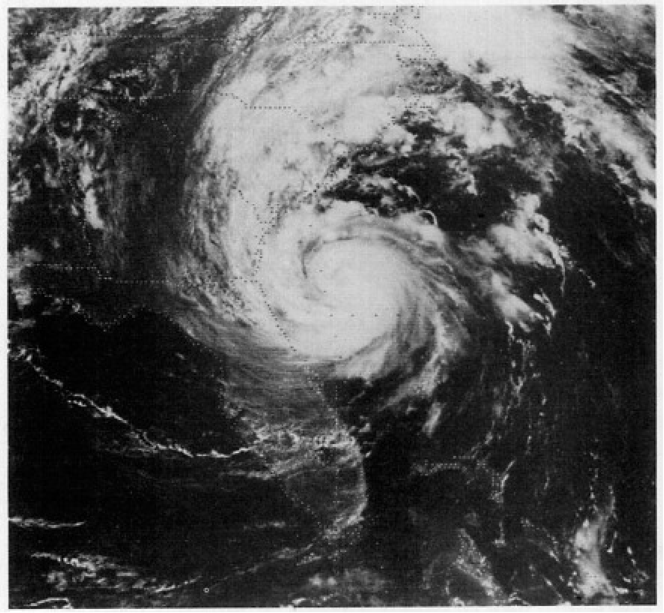

Figure 2.2 1700 UTC 10 September 1984 GOES-West Visible Satellite Image

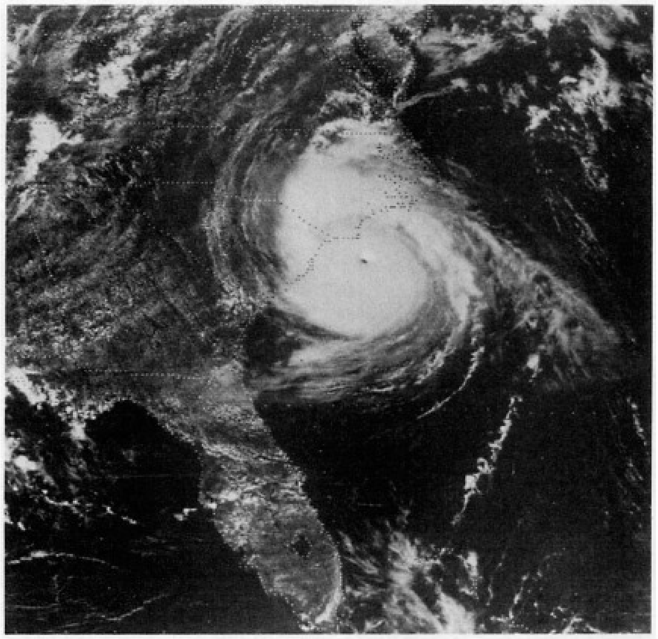

Figure 2.3 1900 UTC 11 September 1984 GOES-West Visible Satellite Image

Hurricane Diana continued to intensify over the next two days, strangely turned out to sea, then looped back and made landfall near Cape Fear, North Carolina at 0700 UTC on 13 September. This unusual track can be seen in Figure 2.4 below.

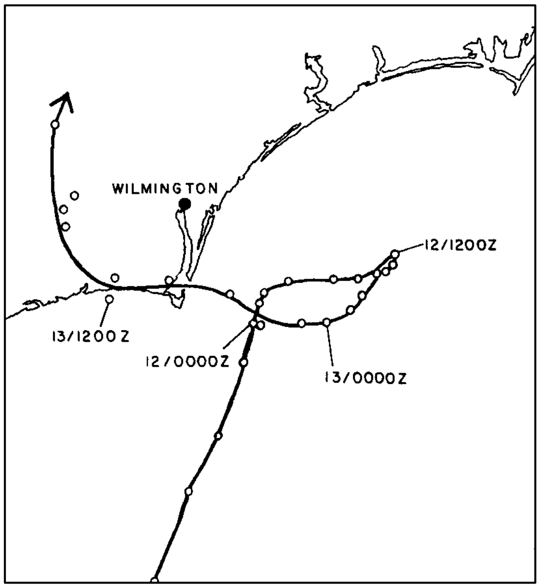

Figure 2.4 Track of Hurricane Diana's Eye from 11—13 September 1971

Upon landfall, central pressure was 949 mb and maximum sustained winds were 59 $ms^{-1}$. Resulting storm surge was 1.7 m at Carolina Beach, North Carolina.

*Elena 1985* (Case 1986)

A well-organized cloud pattern moved off the coast of Africa on 23 August 1985. The dry Saharan air surrounding the storm and the fast moving speed of the system, did not control, or inhibit, formation of this storm. On 28 August Elena was named as it passed over Cuba tracking northwest towards the Gulf of Mexico. With collapsing steering currents and high pressure building in over the eastern United States, Elena made an erratic clockwise track, seen in Figure 2.5, near Cedar Key, Florida, which caused it to weaken slightly.

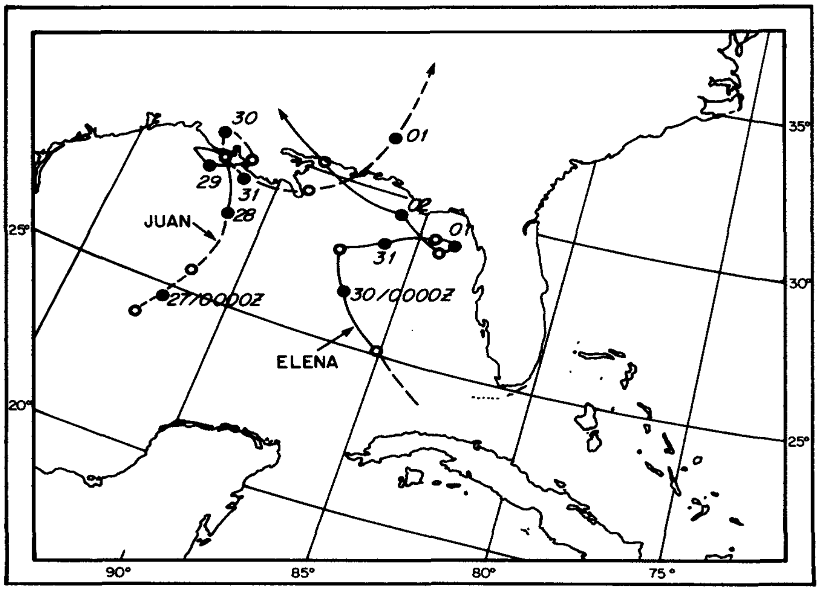

Figure 2.5 Hurricane Elena's Track Prior to Landfall

Then, Elena looped back towards the central gulf coast and made landfall near Biloxi, Mississippi with a central pressure of 959 mb, sustained wind speeds at 47 ms$^{-1}$, and gust up to 61 ms$^{-1}$. Elena caused the largest evacuation to date, nearly one million individuals, and is said to be the reason for so few fatalities and injuries; only four deaths were reported (attributed to falling trees), and no deaths were reported in the areas of landfall. In contrast to the number of injuries, total damage costs were near $1.25 billion.

*Gloria 1985* (Case 1986)

A disturbance, soon to become Hurricane Gloria, began off the African coast on 15 September 1985 and became a tropical depression near Cape Verde on 16 September. Gloria continued as a tropical storm of minimal strength for five days before being upgraded to a hurricane on 22 September. Due to the recent passing of tropical storms

Fabian and Henri, a weakness developed in the western half of the relatively strong subtropical high. Gloria maintained its westerly track along the southern portion of the subtropical high until encountering the area of weakness left by tropical storms Fabian and Henri, and began on a northwesterly track. Having few environmental inhibitors allowed for Gloria to strengthen and reach the lowest recorded pressure over the Atlantic of 919 mb on 25 September. During its northward track, Gloria began to weaken and made landfall on the Outer Banks of North Carolina on 27 September with a central pressure of 942 mb. Since the storm made a south to north approach, the strongest winds stayed well off shore, and due to frictional effects of the land, Gloria weakened and began to accelerate along the New England coast before become extratropical over Maine on 28 September.

*Hugo 1989* (Case and Mayfield 1990)

A cluster of thunderstorms made its way off the coast of Africa on 9 September and became a tropical storm by 11 September and named a hurricane the 13 September. The subtropical high pressure developed a bit of weakness as a low pressure system began to form north of Puerto Rico. Here, Hugo shifted from due west to north-northwest. After moving over Guadeloupe on 17 September, Hugo showed signs of weakening with pressure readings rising. This brief encounter with land, however, did not hinder future intensification. By 19 September the weakness in the subtropical high subsided and Hugo, again under the steering influence of the ridge, was moving northwest. On the 21 September, Hugo gradually steered more northward, in response to low pressure system moving southeast off the Georgia coast, and reintensified. On 22

September, Hugo made landfall at Sullivans Island, South Carolina, near Charleston, with a central pressure of 934 mb and sustained winds at 62 $ms^{-1}$.

Storm surge reports for this storm were sparse, but readings as far north as Hatteras, North Carolina indicated storm surge values to be 1.2 m above predicted tide levels. Forty-nine fatalities were associated with Hugo, along with nearly $7 billion in damages; as of that time, this was the costliest hurricane in United States history.

*Bob 1991* (Pasch and Avila 1992)

Unlike many hurricanes, Bob started as a disturbance near Bermuda. When a weak surface low developed east of the Bahamas, cyclonic circulation of low clouds developed. A depression formed on 16 August and intensified to a tropical storm that day. A deep area of convection formed and Bob became a hurricane on 17 August and was nearly 400 km from Daytona Beach, Florida. With the combination of a strong subtropical high and an upper-level trough over the southeast United States, Bob began to veer to the north and increase in speed. An intensifying Bob, with a well defined eye, passed less than 100 km off the Cape Hatteras coast. Bob continued to move parallel to the eastern coast as a category 3 storm. As it passed New York and reached cooler waters, Bob began to weaken and was only a category 2 storm at landfall on Rhode Island. After passing Rhode Island and Massachusetts, Bob continued to weaken.

At landfall, Bob had a central pressure reading of 964 mb, sustained wind speeds of about 45 $ms^{-1}$ were reported, with gusts up to 55 $ms^{-1}$. High water marks were reported between 3.1—5m. It was noted that these heights were a result of the exposure to the coast. It was also reported that the surge occurred almost two hours after Bob made landfall. Power was lost for an estimated 2.1 million homes and businesses. The total cost of hurricane Bob was $1.5 billion. This includes all damage from North Carolina to Maine.

*Andrew 1992* (Mayfeild et al. 1994)

On 14 August 1992, a tropical wave crossed the Atlantic and was steered toward to the west by a strong subtropical high. Cloud bands associated with the wave began to take on a circulatory pattern and at 1800 UTC 16 August the tropical wave was officially recorded as a tropical depression. Due to weakening upper-level shear, the tropical depression was able to grow to hurricane status. At 1200 UTC, 17 August, Hurricane Andrew was named.

A strong upper-level low steered Andrew away from the Lesser Antilles and brought it into an environment with favorable southwesterly vertical wind shear. Due to the strong southwesterly flow, Andrew was not able to maintain long periods of deep convection. This allowed the central pressure to rise considerably and Andrew dropped back to tropical storm strength on 20 August. Then, large environmental changes occurred, a decrease in upper-level shear due to a splitting low pressure system and a strong steering ridge from the east building in. These changes caused Andrew to rapidly strengthen and reclaim hurricane strength on 22 August. According to Mayfield, Avila, and Rappaport (1992), of the National Hurricane Center, this was this first hurricane to form from a tropical wave in nearly two years. Rapid deepening occurred, according to Holliday and Thomspon (1979), when the central pressure dropped over 72 mb within a 36 hour period. Andrew was a category 4 strength storm as it passed over the northern

Bahamian islands on 22 August and due to the strong subtropical high, stayed on a due west course towards Florida. The central pressure rose from 922 mb to 941 mb after passing over the Bahamas but soon reintensified as it moved over the warm Straits of Florida. At 1010 UTC hurricane Andrew made landfall as a category 5. Eyewall circulation became more vigorous as the storm moved onshore. Boundary layer convergence, according to Mayfield, Avila, and Rappaport (1992), is the cause for this central storm strengthening at landfall.

At landfall, on the Florida coast, Andrew had a recorded central pressure of 922 mb, sustained wind speeds of 63 $ms^{-1}$, gusting up to 76 $ms^{-1}$, and storm surge heights over 5m in Biscayne Bay. Figure 2.6 is a schematic showing storm surge levels along the Biscayne Bar area.

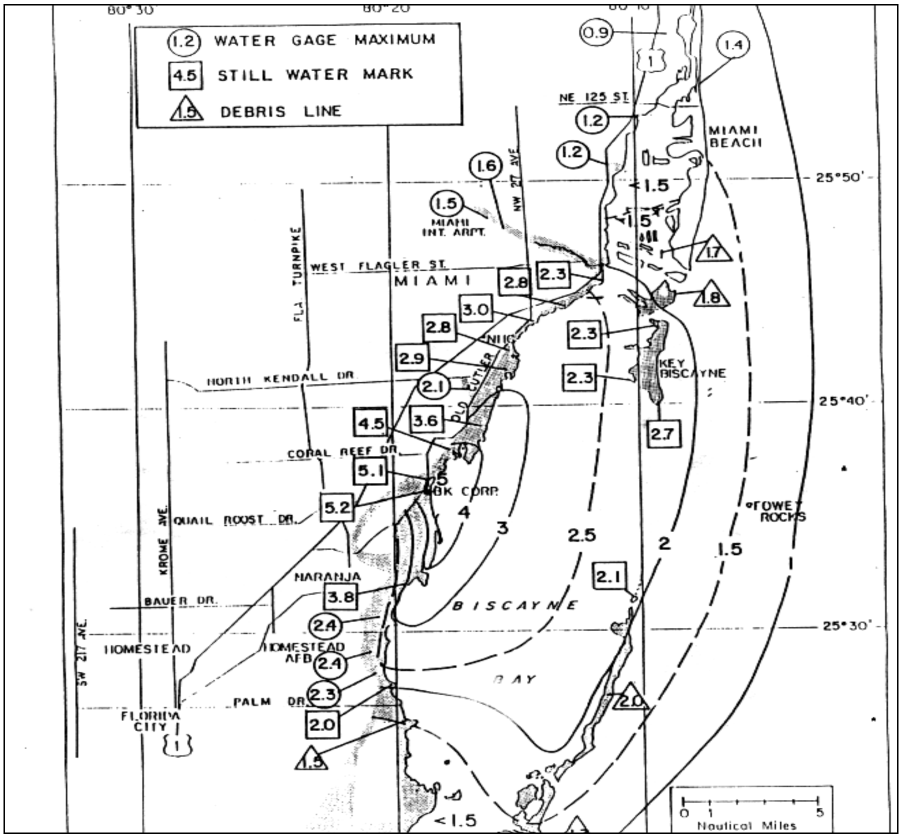

Figure 2.6 Analysis and Representative Observations of Surge Values in Biscayne Bay

This was not the last of Andrew however. Moving directly west, Andrew passed from Biscayne Bay, Florida over the southern Florida tip in four hours. The pressure rose only to 950 mb and weakened only to a category 4 storm. The storm began to turn gradually to the north and take on a more west-northwesterly track. A surface mid-latitude trough approached from the northwest and slowed Andrew to 4 ms$^{-1}$. Losing strength, Andrew made its second landfall at a category 3 storm and affected a sparsely populated town about 35 km west-southwest of Morgan City, Louisiana.

Smaller, yet still significant, storm surge reports of 1.5—2.4 meters were recorded in Louisiana. All in all, damage exceeded the $20 billion mark in the United States with only fifteen deaths associated directly with the storm, but nearly 125,000 individuals were left homeless.

*Bertha 1996* (Pasch and Avila 1999)

A wave moving off the African coast developed into a weak area of circulation on 3 July. Tropical depression status was reached 2 days later and followed along the western periphery of the subtropical pressure ridge. The storm strengthened to a hurricane 3 days later. The track turned more northwestward and continued to strengthen. The gradual shift to a north northwestward track, on the 10th and 11th, brought Bertha parallel to the Florida and Georgia coast. The storm was starting to accelerate and weaken, but just 12 hours before landfall on the North Carolina coast it strengthened quickly.

At landfall, a pressure reading of 977 mb was observed and wind speeds were estimated at 46 $ms^{-1}$. Storm surge values ranged from 0.3-1.8 m. Bertha damaged over 5000 homes, forced the evacuation of 750,000 people and cost $135 million in insured property and cost $270 million in total damage.

*Fran 1996* (Pasch and Avila 1999)

A tropical wave formed off the west coast of Africa during the peak hurricane season on 22 August. Deep convection and surface circulation allowed this storm to become a tropical depression one day later. As this time Hurricane Edouard preceded Fran, and inhibited growth and intensification. The tropical depression slowly moved west over the next few days before being named a hurricane on 29 August, approximately 800 km east of the Leeward Islands. Hurricane Fran weakened to a tropical storm after passing the Islands and once again was impeded by the remains of Hurricane Edouard. Steering currents changed and put Fran on a west-northwesterly track and slowed the forward speed of the storm to 3 ms$^{-1}$. By 31 August Fran was once again a hurricane and the strong subtropical high allowed Fran to continue its west-northwest motion. As Fran moved northeast of the Bahamas 4 September it reached a minimal central pressure of 946 mb. Fran made landfall on 5 September in Cape Fear area of North Carolina.

At landfall, a minimum pressure of 954 mb was recorded, maximum sustained winds were estimated at 51 ms$^{-1}$, and a maximum gust was reported at 61 ms$^{-1}$. Water marks on buildings ranged from 2.7—3.7 m. Roughly 4.5 million were left without power and hurricane Fran is responsible for $3.2 billion in damage.

*Georges 1998* (Pasch et al. 2001)

A tropical wave formed on 13 September and 24 hours later became a well organized area of circulation. A tropical depression was named 15 September and while maintaining a west-northwest track it became a hurricane only two days later. Due to deep convection and a well defined eye Georges began to quickly intensify. By 19 September George became a category 4 hurricane with estimated surface wind speeds of 69.5—77.2 ms$^{-1}$. On 20 September George weakened due to increased vertical wind shear, according to the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin. George made its first landfall in the Lesser Antilles on 21 September. Due to the frictional effects of Cuba and Puerto Rico, George never fully reintensified. George continued to weaken as it moved across the Dominican Republic. Once George moved into the Gulf of Mexico it began to strengthen once again. George brushed across Key West and turned north-northwest and a surface high pressure in the Southeastern United States steered the storm towards the Mississippi coast.

On 28 September George made landfall in Biloxi, Mississippi. Wind speeds at landfall were estimated at 90 kt. and storm surge values range between 1.5—3.7 m. Estimated damage from George was $5.9 billion. George became the most expensive disaster aid effort in 117 years with over $1 million spent from the American Red Cross.

*Floyd 1999* (Lawrence et al. 2001)

Hurricane Floyd started as a tropical wave off the Western African coast that became a tropical depression on 7 September. A strong subtropical high steered the depression in a north-northwestward direction for two days before a being named a tropical storm 8 September. Slowly Floyd strengthened to hurricane status by 10 September. A strong trough developed to the north and steered Floyd more westward towards to the central Bahamas. Floyd started to turn more to the right, after passing near San Salvador and Cat Islands, headed north and paralleled the eastern Florida coast. Floyd then decreased in strength, due to the entrainment of dry air and an increase in lower level vertical shear, and increased in forward speed. Floyd made landfall near Cape Fear, North Carolina early on 16 May.

The maximum intensity of hurricane Floyd was 70 $ms^{-1}$ winds and a minimum pressure of 921 mb. Maximum sustained winds at landfall were estimated at 43 $ms^{-1}$ with maximum gusts up to 62 $ms^{-1}$. Maximum storm surge values were reported at 3.1 m. A total of $1.325 billion was reported for insured property and total damages were totaled at $4.5 billion. An unusual fact about Floyd is the extreme amount of fresh water flooding caused by the storm.

*Isabel 2003* (Lawrence et al. 2005)

Between 1—5 September a tropical wave became an organized area of circulation. Just six hours after being classified as a tropical depression, on 6 September, tropical storm Isabel had formed. By 7 September Isabel became a hurricane and a strong steering subtropical high maintained Isabel on its westward track. For the next three days Isabel strengthened and became a category 5 storm on 11 September with an estimated wind speed of 75 ms$^{-1}$. As the storm held close to the periphery of the subtropical high, it began to move north-northwest as it neared the United States coast. An increase in vertical shear acted to reduce the strength of Isabel to a category 2 storm. Although the size of the storm increased for the next two days, Isabel maintained its category 2 status.

Isabel made landfall near Drum Inlet, North Carolina on 18 September. Wind speed at landfall was 46 ms$^{-1}$ and storm surge values up to 2.5 m were recorded. Storm surge caused a great deal of damage from North Carolina to Maryland. Total damage was estimated at $3.37 billion.

*Charley 2004* (Franklin et al. 2006)

A tropical wave developed off the African coast on 4 August. It was not until 9 August that a well defined area of circulation was observed and a tropical depression was named. One day later the depression became a tropical storm due to low wind shear and good upper-level outflow. Charley became a hurricane as it entered the Caribbean Sea 11 August. The storm took a northwestward track toward western Cuba. Just before making landfall on the Cuban coast, Charley strengthened with wind speeds of 54 $ms^{-1}$ recorded. Charley weakened slightly as it moved through the Straits of Florida. Charley took a sharp directional change to southwest Florida due to an unseasonably strong deep layer trough over the eastern United States. This steering mechanism sent Charley in a north-northeastern direction; Charley intensified rapidly to a category 4 storm before making landfall on the southwast coast of Florida on 13 August. Just 12 hours before landfall Charley's eye became much smaller therefore considerably reducing areas affected by extreme winds.

Maximum sustained winds were near 67 $ms^{-1}$ and Charley's central pressure at landfall was 941 mb. Because of the limited time extreme winds were experienced, storm surge values were fairly modest with a maximum surge of 2 m recorded. Charley caused an estimated $15 billion in damage and, at its time, was the second costliest storm to hurricane Andrew.

*Ivan 2004* (Franklin et al. 2006)

Ivan started when a closed surface-low moved off the African coast into the Atlantic on 31 August. Within two days Dvorak satellite classifications determined a tropical depression had a formed. Three days later, hurricane Ivan was born roughly 1800 km east of the Windward Islands. Ivan continued moving due wast and became the southernmost storm on record. Ivan made landfall on Grenada, Jamaica, and the Cayman Islands. As Ivan passed over each island energy was lost, but Ivan reached category 5 strength on three occasions.  After passing Jamaica and regaining category 5 strength, it was then, 12 September, that the peak intensity of Ivan was recorded; wind speeds were recorded at 75 $ms^{-1}$ with a central pressure of 910 mb.  The subtropical high helped to steer Ivan northwestward into the Gulf of Mexico on 14 September.

Despite moving into an environment usually not conducive to hurricane strengthening, Ivan showed minimal signs of weakening before making landfall west of Gulf Shores, Alabama on 16 September.  At landfall, maximum wind speeds were 54 $ms^{-1}$ and storm surge heights ranged from 3 to 4.6 meters.  As of 2004, Ivan was the third costliest storm with estimated damage totals near $14.2 billion.  Also, Ivan was at hurricane status for ten days, not consecutively, which is the longest a storm has been at hurricane status since 1944.

### *Jeanne 2004* (Franklin et al. 2006)

A benign wave moved off the African coast and headed west.  As it neared the Leeward Islands it became a tropical depression on 13 September.  With a strong subtropical high steering the storm, it continued to follow a west-northwest direction.  A tropical storm was named 24 hours later and made landfall on the Virgin Islands on 15 September.  Prior to making landfall in the Dominican Republic, Jeanne reached hurricane status.  After losing hurricane status and nearly exhausting all energy over Hispaniola, Jeanne developed a new center out ahead of the main storm.  With a new center and a weakening subtropical high, Jeanne moved into the Atlantic, just north of the Bahamas.  Jeanne once again became a hurricane on 20 September.  By 23 September, Jeanne was moving quickly to the west due to a strong high pressure over the United

States. With westward motion and with a presence of more warm water, Jeanne became a major hurricane 25 September.

Jeanne made its final landfall near Stuart, Florida. Maximum wind speeds were estimated to be 54 $ms^{-1}$ and storm surge values were just over 1 meter. Total damage was estimated near $6.9 billion.

*Dennis 2005 (Beven 2005)*

An early season storm, Dennis, started as a tropical wave moving off the African coast in late June. This area of convection moved west and seven days later an area of organized circulation west to of the Windward Islands became a depression. With changing direction to the west-northwest, the depression became a tropical storm and by 7 September, hurricane Dennis was named. Dennis rapidly intensified to a category 4 storm over the open seas of the Atlantic but weakened to a category 3 storm after passing across Cuba. In the Gulf of Guacanayabo, Dennis regained category 4 status and once again passed over Cuba. The second landfall dramatically reduced Dennis' intensity. After emerging in the Gulf of Mexico on 9 July Dennis reintensified and was moving north-northwest. While in the Gulf of Mexico Dennis had reached a maximum wind speed of 125 kt, but dry air entrained into the hurricane weakened the storm just before landfall.

Dennis made landfall on Santa Rosa Island, Florida on 10 July. Maximum wind speed at landfall was 54 $ms^{-1}$ and storm surge values up to 2.13 m were recorded. Figure 2.7 below shows storm-induced tides versus time for different locations along the gulf coast. Total damage was estimated at $1.115 billion.

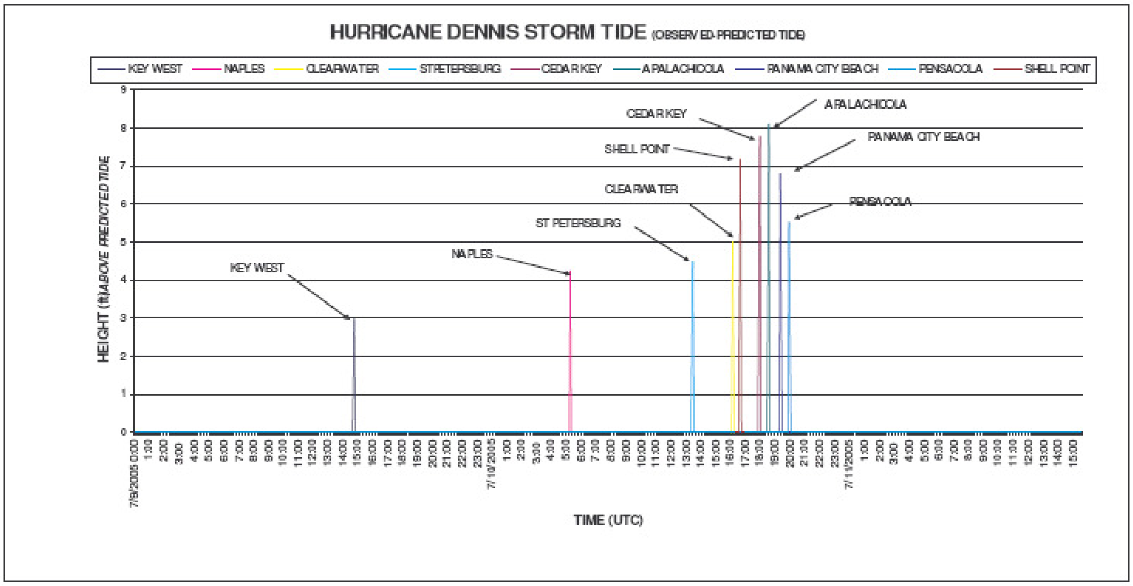

Figure 2.7 Storm-induced tides (surges) for Hurricane Dennis plotted versus time for the stations along the Florida west coast and Apalachee Bay. (Image Courtesy of the TPC Storm Surge unit)

*Katrina 2005* (Knabb et al. 2006)

The origin of Katrina was rather unusual; it began when a tropical wave, a tropical depression, and a pre-existing trough combined. A tropical depression, soon to be Katrina, formed on 22 August over the Bahamas. Circulation became better organized and deep convection occurred overnight and tropical storm Katrina was born 24 August. Due to a strong area of high pressure over the Gulf of Mexico Katrina took a westward track from the Bahamas to the Gulf. Katrina became a hurricane by 25 August and just hours later Katrina made its first landfall on the southeastern Florida coast as a category 1 storm.

Katrina spent a substantial amount of time over land, nearly raining itself out, and became a tropical storm before moving back into the open water of the Gulf of Mexico.

As the storm emerged in the southeastern Gulf, it was taking a west-southward track around the southern half of the strong area of high pressure. This area of high pressure acted to reduce upper-level wind shear while supporting upper-level outflow needed for strengthening. Over the next 48 hours, while moving more east-northeast, Katrina returned to hurricane status and quickly intensified to a category 5 storm. During this time Katrina experienced an eye wall replacement and nearly doubled in size. Just 18 hours prior to landfall, rapid weakening occurred; this is possibly a result of the eye wall replacement, which disrupted the initial structure of storm.

Katrina made landfall as a category 3 storm near Buras, Louisiana on 29 August. Wind speeds were estimated at 56 $ms^{-1}$ and storm surge values were record breaking, almost 9.14 m. Katrina became one of the costliest storms on record resulting in $81 billion worth of damage, this according to an article written only 4 months after Katrina. Much later reports suggest that Katrina's final damage was in excess of $200 billion.

*Rita 2005* (Knabb et al. 2006)

A wave of energy moved off the African coast on 7 September and moved across the Atlantic for the next ten days without much change. After interacting with a pre-existing storm system over Cuba, the tropical wave showed signs of circulation. Due to decreased vertical shear and a strong upper- level trough, organization increased and a tropical depression formed on 18 September. Within 24 hours a tropical storm had formed and was moving west-northwest from the Bahamas. Rita was slow to gain strength and turn more westward as a result of the strong subtropical high. Rita approached the Florida straights on the 20 September but did not have a well defined eye and passed just south of the Florida Keys. As Rita moved into the Gulf of Mexico it rapidly intensified and became a category 3 storm by 21 September. Warm Gulf water and weak wind shear aloft enabled Rita to strengthen to a category 5 storm by 22 September; at this time Rita was roughly 550 km southeast of the Mississippi River moving west-northwest. Hurricane Rita's diameter increased drastically after an eyewall replacement occurred. Although internal structure had changed, Rita did not reintensify. However, weakening did occur due to temperature differences in the water and increased southerly winds aloft. This caused Rita to weaken to a category 3 on 23 September.

Rita made landfall in between Johnson's Bayou and Sabine Pass. At landfall, Rita had wind speeds of 51 $ms^{-1}$ and maximum storm surge values were recorded at 1.52 m. Resulting storm surge values were recorded miles inland and substantial flooding occurred. Estimated damages were about $10 billion.

*Wilma 2005* (Pasch et al. 2006)

Wilma, unlike many tropical systems, started rather unusually. A large weather disturbance, instigated by an area of diffluent flow, developed in the Caribbean Sea. By 15 October, Dvorak satellite classification indicated a tropical depression had formed with an area of deep convection moving strangely to south-southwest. Due to a weak steering flow in the Gulf of Mexico, it took two days for the tropical depression to be classified as a tropical storm. On 19 October, the tropical storm made a sharp turn to the northwest and was set on a track for the Yucatan Peninsula. Within 24 hours, Wilma went from a tropical storm to a category 5 hurricane. Reconnaissance aircraft indicated record breaking measurements starting with the smallest eye with a diameter of 3.7 km and a record low pressure of 882 mb.

Wilma made her first landfall, as a category 4 storm, on 21 October on the island of Cozumel. After crossing the Yucatan Peninsula, Wilma veered to the north-northeast and lost a considerable amount of strength, at this point it was barely a category 2 storm. Although there were fairly strong winds aloft, Wilma strengthened quickly to a category 3 before making landfall on 24 October near Cape Romano, Florida. At landfall, wind speeds were in excess of 51 $ms^{-1}$ and recorded storm surge values ranged from 1.22—2.74 m. It is noted, however, that higher storm surge values probably occurred in rural areas. Wilma caused the largest power outage that south Florida had ever seen, with 98 percent of users without power. Wilma became the third costliest hurricane at $20.6 billion.

# CHAPTER III

# DATA AND METHODS

The purpose of this study is to determine variability, if any, between storm surge heights and category 2, or greater, hurricanes with respect to location. This study was conducted by:

1) Determining study area
2) Gathering hurricane data
3) Reducing data set based upon hurricane track, surface observations, and availability of data
4) Calculating differences of means between locations

## Study Area

The entire study area for this project follows the coastline from Eastport, Maine to Brownsville, Texas with four major divisions, thus creating five separate basins. These delineations were determined based upon coastal concavity, geographic similarities, basin structure, and location of hurricane landfall.

One of the main factors determining regions was location of landfall; this was to ensure that all storm surge data for a single storm fell within a single basin and were not split between two basins. All locations affected by a category 2, or greater, storm, for which a storm surge value was recorded, were plotted by latitude and longitude. This spatial plot made it possible to identify exactly where data were recorded, and to define basins accordingly so that data do not over lap between basins.

This plot was also used to determine if there existed any geographical features that could influence the storm surge height for that specific location. Geographical features such as river inlets, small canals, or lakes can positively or negatively affect storm surge, and therefore, skew the overall distribution of storm surge data. Only storm surge heights recorded for coastal locations were used for this study. Figure 3.1 shows an example of data points that were purged from this study due to their location on a river inlet. With the consideration of data overlap and elimination of non-coastal surge data, the final study area was determined. The study area includes two major regions: the Gulf of Mexico region, divided into three basins, and the Atlantic region, divided into two basins (Figure 3.2).

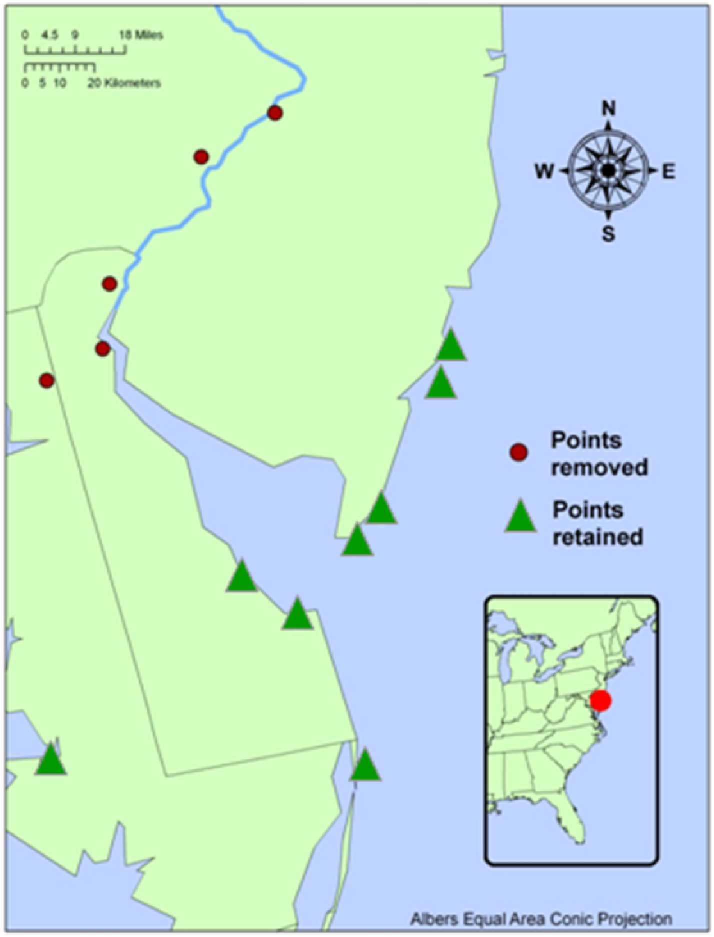

Figure 3.1 Non-Coastal Surge Data Removed from Study

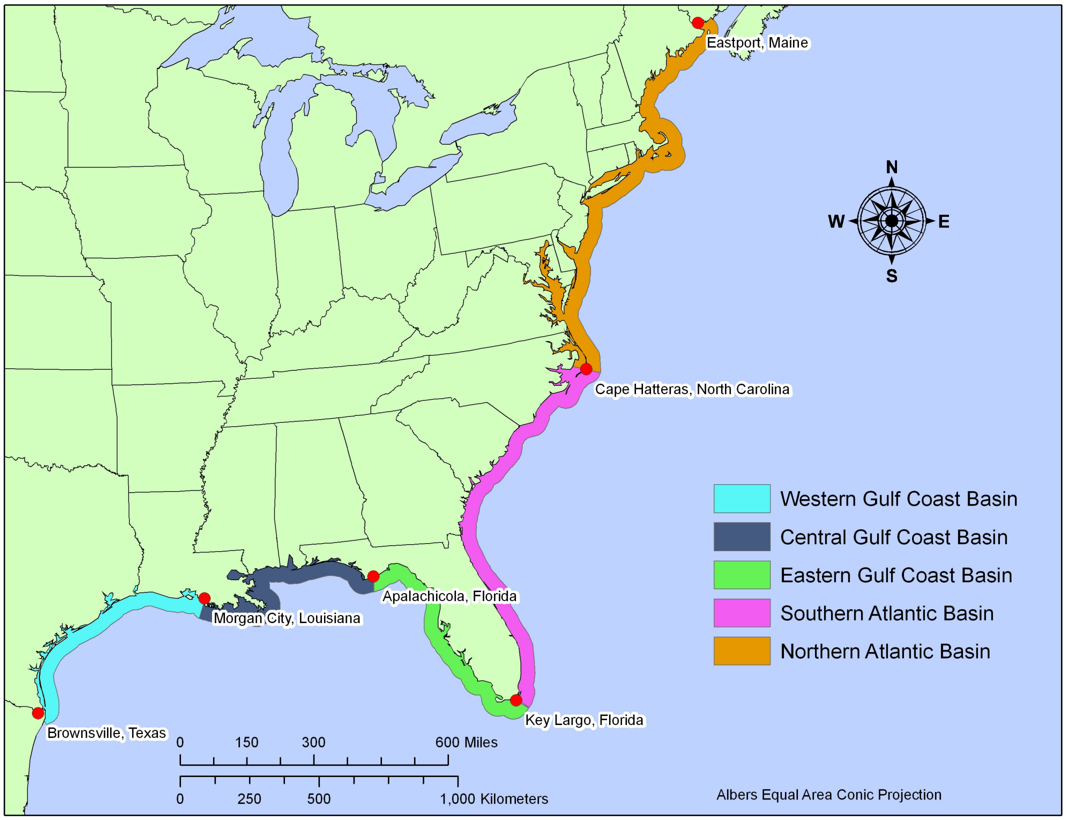

Figure 3.2 Study Area with Basin Delineations

The first basin, the Western Gulf Coast Basin extends from the city of Brownsville, Texas, to Morgan City, Louisiana. From Morgan City, Louisiana, to Apalachicola, Florida, is the Central Gulf Coast Basin and this delineates basin two. The third basin, the Eastern Gulf Coast Basin, is defined from Apalachicola, Florida, to Key Largo, Florida. The fourth basin, the Southern Atlantic Basin, includes the eastern Florida coast from Key Largo, Florida, to Cape Hatteras, North Carolina. The fifth and final subdivision, the Northern Atlantic Basin, includes the remaining coastal states from Cape Hatteras to Eastport, Maine.

## Hurricane Data

After determining the study area, data were acquired. All land-falling hurricanes during 1969–2005, with a Saffir-Simpson categorical ranking of 2 or greater, were identified. Then, the annual Atlantic hurricane summary, issued in the *Monthly Weather Review,* was collected for corresponding years, in which the above criteria are met.

In order to maintain the integrity of this project, and the data therein, specific criteria were used to ensure that the most accurate storm surge data were used and that the data were consistent throughout the entirety of this study. These criteria include:

1) Locations must be affected directly by a land-falling storm
2) Each storm must have at least five locations with recorded storm surge or storm tide values
3) Storms must have at least one location with both storm surge and storm tide values

As a result of the second criterion, many storms cannot be used for the purpose of this research because storm surge data are not available.

## Hurricane Tracks

Hurricane tracks were viewed for all storms category 2, or greater, in order to determine where hurricanes made direct landfall. Locations that reported storm surge from indirect landfall, or sea-falling hurricanes, were excluded. For example, the detailed summary for Hurricane Frances, has more than five locations with storm surge reports; however, less than five of these reports are for locations on the eastern Florida coast, where Frances made initial land fall. Most reports are from western Florida, which is considered sea-falling data, thus, Frances was removed from this study. Subsequently, the third basin, the Eastern Gulf Coast Basin, has fewer storms because most storm surge reports made in the Eastern Gulf Basin are a result of hurricanes that made landfall on the Atlantic coast of Florida and crossed the state from east to wast.

## Surface Observations

Reviews of the surface observations, found in *Monthly Weather Review*, were conducted in order to gather storm surge or storm tide data. The detailed meteorological data, located in the annual storm summaries for each storm, include the following surface observations: specific city and state location, pressure (with corresponding date and time), sustained wind speed, peak gust (with corresponding date and time), storm surge, storm tide, and total rainfall. All of this information is given in table form in the Appendix, which shows the meteorological data tables, from *Monthly Weather Review*, used for every storm in this study. It was found, however, that many storms lack adequate storm surge data or enough storm surge data to provide confident results. So, in order to maintain the accuracy of the results, only storms having a minimum of five locations with storm surge or storm tide data were used for this study.

## Storm Surge Data

With the final 28 hurricanes determined, storm surge data were collected or estimated. This study requires the comparison of storm surge data and not storm tide data, hence the acquisition of actual storm surge data is most important. Referencing the annual storm summaries, many storm records lack sufficient storm surge data but provide ample storm tide, which can be used to estimate storm surge values. Nevertheless, in order to maintain the accuracy of the results, actual storm surge data are ideal. Therefore, it was important to first attempt to locate actual storm surge data for locations that were not recorded in the *Monthly Weather Review*; this resulted in contacting specific individuals within agencies associated with the collection of hurricane data.

First, the NOAA/NWS/NCEP/TPC/National Hurricane Center Science and Operations Officer (SOO) was contacted via email regarding the whereabouts of storm surge data. According to the NHC SOO, "There does not exist at this point a storm surge height database." Despite the lack of storm surge data available from a single database, there are efforts by Florida International University Hurricane Center to develop this database in the near future (Landsea 2006, personal comm.). The NHC SOO advised the use of the annual storm summaries in the *Monthly Weather Review* to locate storm surge data.

Without a homogeneous database and *Monthly Weather Review* storm summaries lacking adequate storm surge records, a more localized search was necessary. Local NWS offices were contacted in search of additional storm surge data for specific storms affecting that particular location. For many locations, responses would lead back to the annual storm summaries. Some would suggest additional literature written for specific storms and recommend contacting the author's of these papers. Unfortunately, additional research is generally conducted for well-known storms, or record-breaking storms, so every category 2 or 3 storm that has made land-fall may not have the same, or even similar, documentation.

With so little storm surge data available, it was necessary to take the storm tide data that were given in the annual storm summaries, found in the *Monthly Weather Review,* and calculate surge height. According to the National Oceanic and Atmospheric Administration (NOAA) glossary, storm tide is the combined effect of storm surge, existing astronomical tide conditions, and breaking wave setup (http://www.csc.noaa.gov/rvat/glossary.html). For this reason, tide information was needed to determine surge heights, however, these data are not readily available for many locations from agencies/organizations responsible for data collection and recording.

After contacting the NOAA, National Ocean Service Oceanographer/Analyst, it was determined that all tide data that are available can be found in the on-line records. Only under certain circumstances, where a location has been recording data for many decades, are the earlier data found in an in-house database. Unfortunately, tide data available through NOAA's Tides and Currents website (http://tidesandcurrents.noaa.gov/) were not useful in this study, due to incomplete or inconsistent records.

Attempts to locate either storm surge or tide data continued with researchers within the Hurricane Research Division of the National Hurricane Center. Here, a number of researchers were questioned, but nobody could offer help finding data. Finally, the storm surge data search came full circle when a researcher from the National Hurricane Center sent the storm surge request to the only individual expected to know how to acquire these data, the NOAA/NWS/NCEP/TPC/National Hurricane Center Science and Operations Office.

## Storm Surge Estimations

Since *Monthly Weather Review* storm records lack sufficient storm surge data and attempts to gather actual storm surge data from other agencies proved unsuccessful, although not ideal, it was possible to estimate storm surge given the storm tide data. The estimations were made by taking the given storm tide height and subtracting the astronomical tide, this results in an estimated storm surge height for a location.

At this point, without specific storm surge data or astronomical tide information for many locations, the average high and low tides were estimated for each location. Tidal information was found in the Geodetic Survey making it possible to use interpolation, along with the mean tides, to estimate specific tide, and thus, estimate storm surge.

In order to accurately interpolate the astronomical tide, a storm's record must contain at least one location with both a storm surge and storm tide value. Thus, storms having record of only storm tide, without any storm surge data, were removed from this study.

Storm surge estimations begin with a location having both storm surge and storm tide data. The storm surge value is subtracted from the storm tide to determine the tide height for that particular time at that specific location. Then, it is determined where the tide occurs, between high and low tide, based upon the information given by the Geodetic Survey. Using this information, and simple interpolation, it is possible to determine the tide at locations with recorded storm tide data.

For example:

1) Both a storm surge and storm tide value must be given for a location.
2) By subtracting the storm surge from the storm tide, a tide value is determined for that location.
3) From the mean tide data given by the Geodetic Survey, it is determined whether the tide value calculated in Step 2, occurred at high or low tide.
4) For locations not having surge data, but having storm tide data, interpolation is used to calculate storm surge.
5) Since it is determined in step 3 when the tide occurred at one location (i.e.: high-high, high, low, or low-low tide) it can be assumed that other cities nearby have the same tide occurring at that time.
6) Subtracting the mean tide value for locations, at said tide, from the storm tide value, the storm surge can be estimated.

**Statistical Analysis**

After gathering, or estimating, all the storm surge data, storm surge averages were calculated for each storm using the 5 highest storm surge values. First, the average of the 5 storm surge values for each storm was calculated. Theses averages were compared between basins and a difference of means were calculated. Likewise, an average of three surge values were calculated; these three values include the maximum storm surge for a storm and the two surge values, one to the right and one to the left, closest to the max surge location. Then, all maximum storm surge values were compared between basins with a difference of means calculated. Next, an average storm surge value for the same category storm within one basin was compared to average storm surge value for the same category storm in another basin. For example, all storm surge values for category 2 storms in Basin 1 were averaged then compared with the average storm surge value for all category 2 storms in Basin 4.  Finally, an average of all storm surge values for one category storm were averaged for each region and a comparison made between the difference in means between the Gulf Coast Region and East Coast Region.

# CHAPTER IV

# RESULTS

The purpose of this project is to test for variation in storm surge heights for like-category storms between the Gulf Coast Region and the Atlantic Coast Region. Since the most damaging part of a hurricane is storm surge (Hoover 1957), not wind, which singularly defines the Saffir-Simpson hurricane scale, it is important to understand variables that contribute to storm surge heights. Henceforth, the categorical ranking of a hurricane can be misleading as to potential damage that could occur from that storm.

Although there are several variables that can be studied for this topic, the focus of the project is geography. It is important to compare storm surge heights for different locations struck by storms with the same category in order to better identify coastal similarities that influence storm surge. Results do indicate that there is variation in storm surge height between the Gulf Coast Region and the Atlantic Coast Region for like-category storms. Results also show a small variation in storm surge heights between storms of different categories for the Atlantic Coast Region; the Gulf Coast Region, on the other hand, has a greater variation in storm surge heights between categories.

Results show that category 2, 3 and 5 storms produce significantly higher maximum storm surges in the Gulf Coast Region than the Atlantic Coast Region.

Conversely, storm surge heights resulting from category 4 storms are, on average, slightly higher in the Atlantic Coast Region. These results can be seen in Figure 4.1.

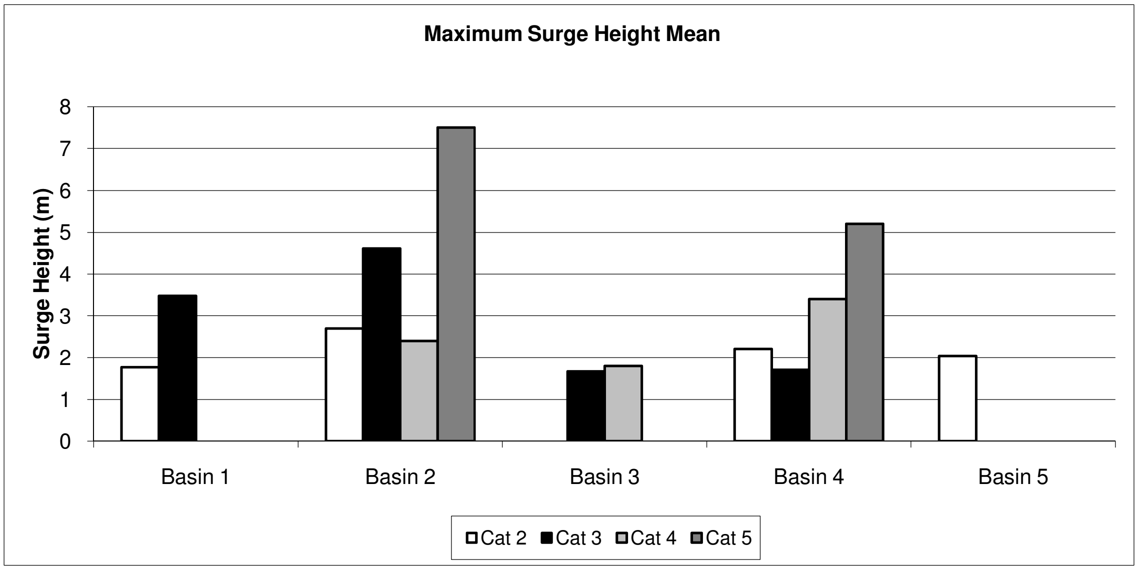

Figure 4.1 Mean Maximum Storm Surge per Basin for Category 2, 3, 4 and 5 Hurricanes

When adding surge values that occurred to the right and left of the location of maximum surge with the maximum surge value, results are similar, although not as impressive. Figure 4.2 below shows a similar plot to Figure 4.1. This plot also shows that there is a very small surge height variation between categories for basin 4 storms. Interestingly, category 5 storms in basin 4 actually had the lowest storm surge heights. The difference in storm surge heights between category 2, 3 and 5 storms in basin 4 was less than 0.10 m. Category 4 storm surge heights were just less, or right at, 1.0 m difference from the category 2, 3 and 5 surge averages.

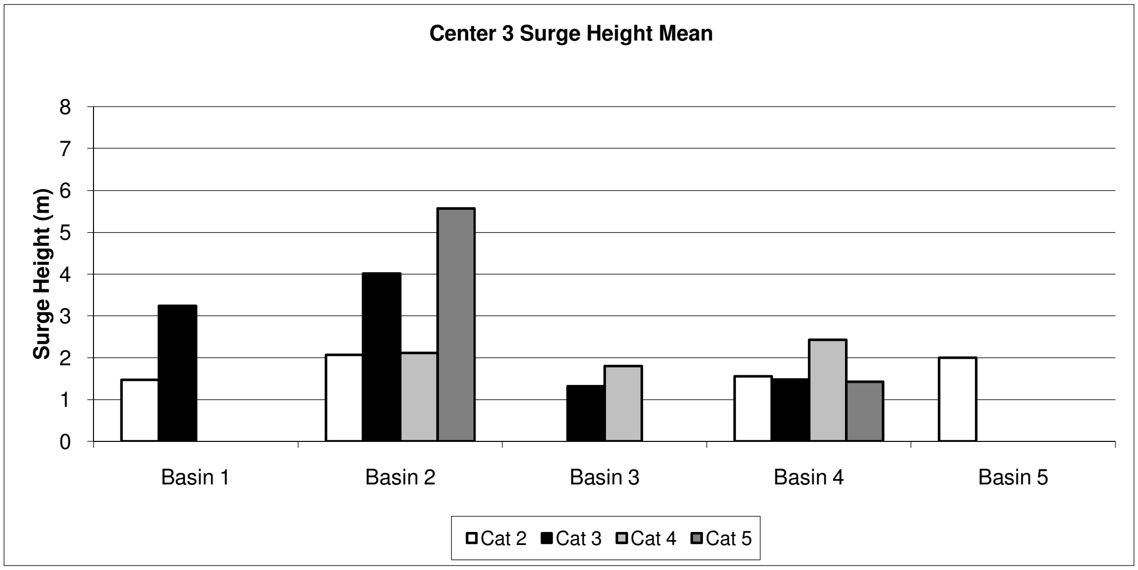

Figure 4.2 Center 3 Storm Surge Mean per Basin for Category 2, 3, 4 and 5 Hurricanes

A similar plot is produced, Figure 4.3, when averaging the top 5 storm surge heights. Both Figure 4.2 and Figure 4.3 are beneficial because they act to validate the initial findings found in Figure 4.1. There is not a substantial difference in these plots, other than that more storm surge values lower the overall storm surge height. In basin 3, there was not enough data to include category 4 storms for comparison.

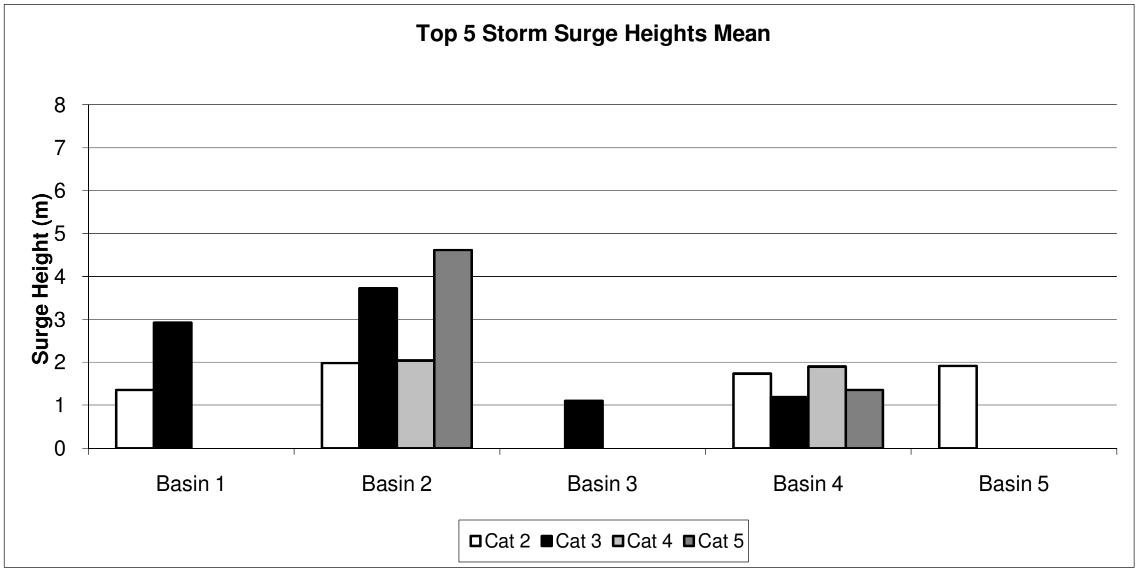

Figure 4.3 Top 5 Storm Surge Mean per Basin for Category 2, 3, 4 and 5 Hurricanes

### Category 2

When comparing regions, Gulf Coast to Atlantic Coast, the results in Table 4.1 show that for category 2 storms there is a higher maximum storm surge average for the Gulf Coast Region, as well as the mean of the top 5 surge values and the center 3 mean.

Table 4.1 Category 2, Mean Surge Heights Gulf Coast Region and Atlantic Coast Region

| | **Maximum Surge Mean (m)** | **Top 5 Mean (m)** | **Center 3 Mean (m)** |
|---|---|---|---|
| **Gulf of Mexico Region**<br>**(Basin 1, 2, & 3)** | 2.23 | 1.98 | 2.07 |
| **Atlantic Coast Region**<br>**(Basin 4 & 5)** | 2.13 | 1.82 | 1.78 |

When comparing storm surge heights between basins, results show that basin 2, Central Gulf Coast Basin, has, on average, a higher storm surge than basin 4, Southern Atlantic Coast Basin, and basin 5, Northern Atlantic Coast Basin. Although results do indicate a higher maximum storm surge occurs in basin 2, it is only 0.49 m higher than basin 4, and only 0.66 m higher than basin 5. The top-5 mean and center-3 mean are almost 1.00 m greater in basin 2 than both basins 4 and 5. Surge height averages for basin 1 were lower than any other basin. These results can be seen in Table 4.2 below.

Table 4.2 Category 2, Mean Surge Heights Basin 1, 2, 3, 4 and 5

| | **Maximum Surge Mean (m)** | **Top 5 Mean (m)** | **Center 3 Mean (m)** |
|---|---|---|---|
| **Basin 1** | 1.77 | 1.33 | 1.47 |
| **Basin 2** | 2.70 | 2.62 | 2.27 |
| **Basin 3** | — | — | — |
| **Basin 4** | 2.21 | 1.73 | 1.56 |
| **Basin 5** | 2.04 | 1.91 | 2.00 |

## Category 3

When comparing regions, Gulf Coast to Atlantic Coast, the results in Table 4.3 show that for category 3 storms there is a higher Maximum, Top 5 Mean and Center 3 Mean storm surge average for the Gulf Coast Region. On average, storm surge heights are 1.5+ m greater in the Gulf Coast Region than the Atlantic Coast region.

Table 4.3 Category 3, Mean Surge Heights Gulf of Mexico Region and Atlantic Coast Region

| | **Maximum Surge Mean (m)** | **Top 5 Mean (m)** | **Center 3 Mean (m)** |
|---|---|---|---|
| **Gulf of Mexico Region** | 3.15 | 2.50 | 2.77 |
| **Atlantic Coast Region** | 1.71 | 1.19 | 1.48 |

With the removal of anomalous Katrina (2005), the results still indicate a greater storm surge in the Gulf Coast Region, more specifically basin 2, than the Atlantic Coast Region. In fact, there is only a variation, on average, of less than 0.5 m; these results are shown below in Table 4.4.

Table 4.4 Category 3, Mean Surge Heights Gulf of Mexico Region and Atlantic Coast Region, Without Katrina (2005)

| | **Maximum Surge Mean (m)** | **Top 5 Mean (m)** | **Center 3 Mean (m)** |
|---|---|---|---|
| **Gulf of Mexico Region** | 2.86 | 2.26 | 2.52 |
| **Atlantic Coast Region** | 1.71 | 1.19 | 1.48 |

Comparing variations in storm surge height between basins, results in Table 4.5 show that basins 1, 2, and 3 are much greater than basins 4 and 5. The basin with the highest overall average is basin 2. The drastic difference in storm surge height averages between basin 2 and other basins could be the simple fact the Hurricane Katrina (2005), a category 3 storm at landfall, fell in the Central Gulf Coast Basin, or basin 2. The bolded and italicized values, in Table 4.5, are storm surge averages without Katrina (2005).

Table 4.5 Category 3, Mean Surge Heights Basin 1, 2, 3, 4 and 5 (*Surge *Averages without Katrina (2005) Values*)

| | **Maximum Surge Mean (m)** | **Top 5 Mean (m)** | **Center 3 Mean (m)** |
|---|---|---|---|
| **Basin 1** | 3.48 | 2.92 | 3.24 |
| **Basin 2** | 4.30 (****3.44***) | 3.48 (****2.76***) | 3.75 (****3.00***) |
| **Basin 3** | 1.67 | 1.1 | 1.71 |
| **Basin 4** | 1.71 | 1.19 | 1.48 |
| **Basin 5** | — | — | — |

## Category 4

When comparing regions, Gulf Coast to Atlantic Coast, the results in Table 4.6 show that for category 4 storms there is a higher Maximum and Center 3 Mean storm surge average for the Atlantic Coast Region. Although the Atlantic Coast was higher on average, by just under 1.00 m for the maximum storm surge, it was only about 0.40 m differences when comparing the Center 3 Mean storm surge values. Conversely, when comparing the averages of the top 5 mean, the Gulf Coast was only slightly higher, at just over 0.14 m than the Atlantic Coast Region.

A comparison between basins can be seen in Table 4.7 and due to the lack of land-falling storms in basin 5, the results for Atlantic Coast Region and basin 4 are the same. There were 2 basins, 2 and 3, included for the Gulf Coast Region.

Table 4.6 Category 4, Mean Surge Heights Gulf of Mexico Region and Atlantic Coast Region

| | **Maximum Surge Mean (m)** | **Top 5 Mean (m)** | **Center 3 Mean (m)** |
|---|---|---|---|
| **Gulf of Mexico Region** | 2.10 | 2.04 | 2.00 |
| **Atlantic Coast Region** | 3.40 | 1.90 | 2.43 |

Table 4.7 Category 4, Mean Surge Heights Basin 1, 2, 3, 4 and 5

| | **Maximum Surge Mean (m)** | **Top 5 Mean (m)** | **Center 3 Mean (m)** |
|---|---|---|---|
| **Basin 1** | — | — | — |
| **Basin 2** | 2.40 | 2.04 | 2.12 |
| **Basin 3** | 1.80 | — | 1.80 |
| **Basin 4** | 3.40 | 1.90 | 2.43 |
| **Basin 5** | — | — | — |

## Category 5

When comparing regions, Gulf Coast to Atlantic Coast, the results in Table 4.8 show that for category 5 storms there is a higher Maximum, Top 5 Mean and Center 3

Mean storm surge average for the Gulf Coast Region. Due to the limited number of category 5 storms, only basins 1 and 4 were compared for this part of the study. Thus, the results for region to region and basin to basin comparisons, seen in Table 4.9, are the same.

Table 4.8 Category 5, Mean Surge Heights Gulf of Mexico Region and Atlantic Coast Region

| | **Maximum Surge Mean (m)** | **Top 5 Mean (m)** | **Center 3 Mean (m)** |
|---|---|---|---|
| **Gulf of Mexico Region** | 7.50 | 4.62 | 5.57 |
| **Atlantic Coast Region** | 5.20 | 4.44 | 4.70 |

Table 4.9 Category 5, Mean Surge Heights Basin 1, 2, 3, 4 and 5

| | **Maximum Surge Mean (m)** | **Top 5 Mean (m)** | **Center 3 Mean (m)** |
|---|---|---|---|
| **Basin 1** | — | — | — |
| **Basin 2** | 7.50 | 4.62 | 5.57 |
| **Basin 3** | — | — | — |
| **Basin 4** | 5.20 | 4.44 | 4.70 |
| **Basin 5** | — | — | — |

Furthermore, Figure 4.4 shows a distinct storm surge difference in storms making landfall in basin 2, the Central Gulf Coast basin. When plotting intensity values for all storms in the Gulf Coast and Atlantic Coast region, the Central Gulf Coast Basin, basin 2, storms have noticeably higher surge values. The maximum storm surge values for basin 2 storms were still greater than some storms with higher intensities.

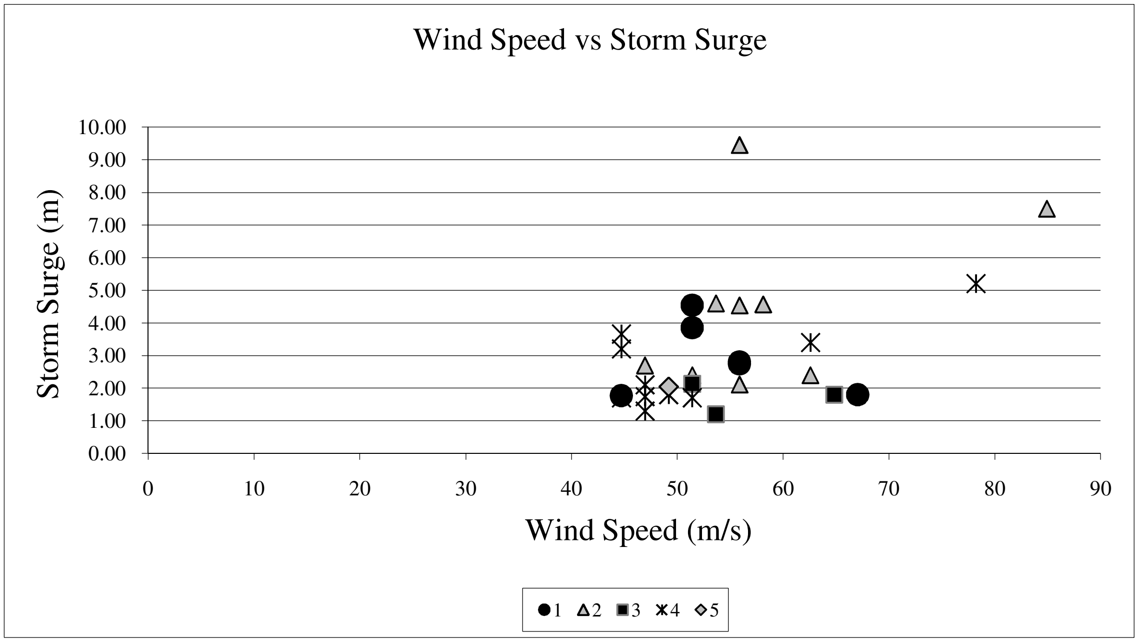

Figure 4.4 Maximum Storm Surge Height vs. Storm Intensity (at landfall)

Figure 4.5 shows a positive, near linear, trend in the increase of wind to surge height. The trend lines also indicate that there might be a slightly higher surge value in the Gulf of Mexico, but due to limited values, there is not significance here.

Figure 4.5 shows the normalization of regions, but breaking the regions into basins, figure 4.6 shows the surge height trend, normalized values. Even within the basins, similar results are found. Again, limited data affected the linear trend for basin 1 and 3, as basin 1 shows a negative trend and basin 3 shows no rise or fall in height with increased wind speed. The two basins with the most data points are basins 2 and 4 and both of those trend lines show positive trending with between surge height and wind speed.

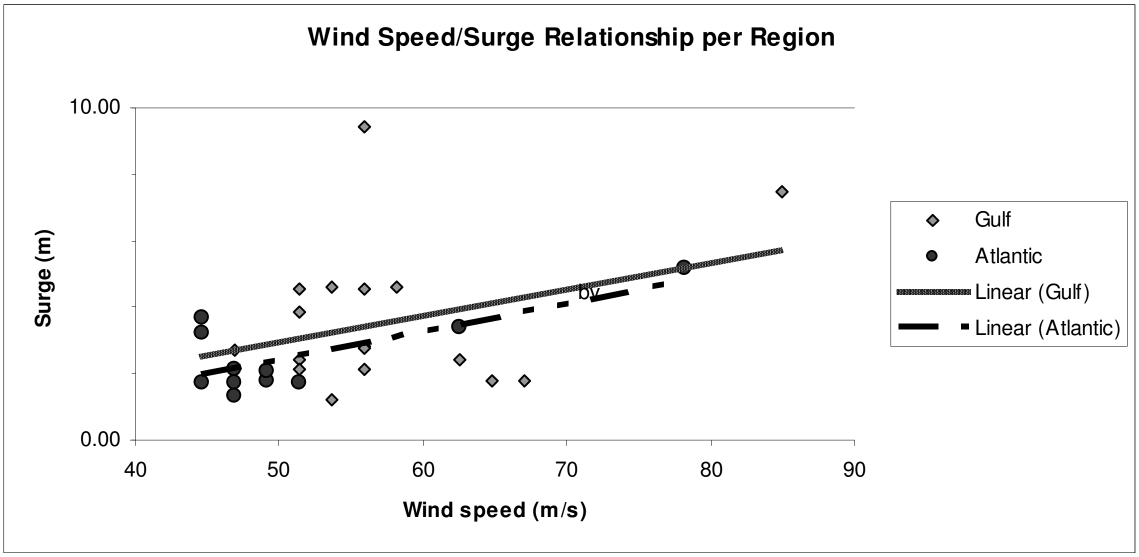

Figure 4.5 Normalized Surge Values between the Gulf and Atlantic Regions

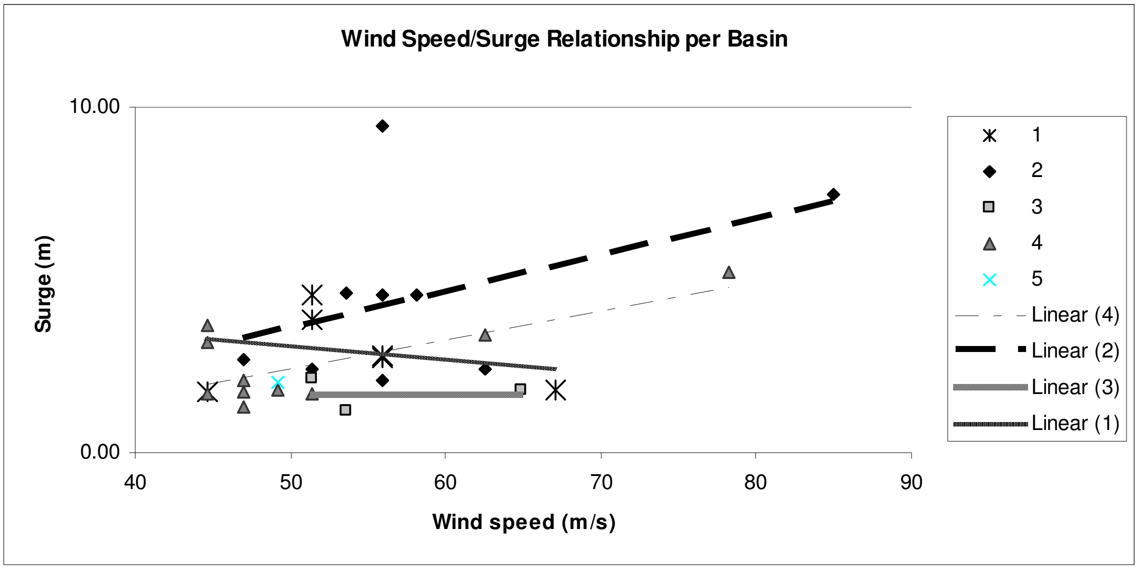

Figure 4.6 Normalized Surge Values between Basins

Another interesting find was the height of storm surge per unit of wind speed. Figure 4.6 shows that basin 2 and 4 have the most noticeable change in height with the increase in wind speed.  Basin 3 is not as impressive, but this is most likely due to the limited amount of surge data collected for this basin.  Although basin 1 shows a negative trend line, one storm could be skewing the overall data results. Of the 6 storms used for determining wind speed/surge relationship for basin 1, one storm with the maximum wind speed also had the lowest surge value. Without the inclusion of this one data point, the line would actually trend upward, very similar to basin 2 and 4.

Although, there is an overall negative relationship between wind speed and surge in basin 1, based on Figure 4.6, basin 1 actually has the second highest normalized value seen in Figure 4.7.  Basin 4 ranks third in height change per meter per second of wind speed with basin 1 having the highest change in height with change in wind speed (Figure 4.7).

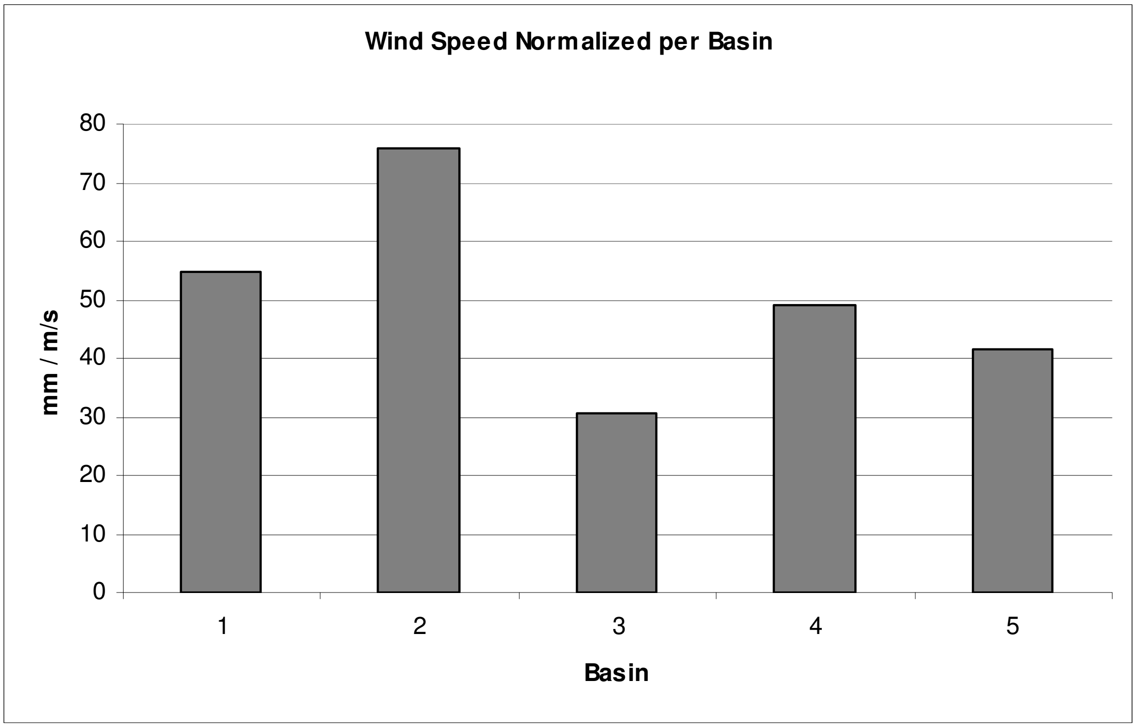

Figure 4.7 Millimeter of Surge per Meter/Second Wind for Basin 1—5

## Statistical Analysis

Statistics further validate that there is a significant difference in storm surge heights between the Gulf Coast Region and the East Coast Region. The following tables, 4.10 and 4.11, show the difference in means and p values for each basin comparison. Due to the lack of data for category 4 and 5 storms, only category 2 and 3 storms were used for statistical analysis. The bolded and italicized values indicate statistical significance.

Table 4.10 Mean Differences and p Values Between Basins for Category 2

| | | **Maximum** | **Top 5** | **Center 3** |
|---|---|---|---|---|
| **Basin 1, 2, 3 and 4, 5** | Mean Difference | 0.10 | 0.16 | 0.29 |
| | p Value | 0.48 | 0.61 | 0.55 |

Table 4.11 Mean Differences and p Values Between Basins for Category 3

| | | **Maximum** | **Top 5** | **Center 3 Mean** |
|---|---|---|---|---|
| **Basin 1 and 2** | Mean Difference | 0.82 | 0.56 | 0.51 |
| | p value | 0.59 | 0.60 | 0.76 |
| **Basin 1 and 3** | Mean Difference | 1.81 | 1.82 | 1.53 |
| | p value | 0.94 | 0.72 | 0.90 |
| **Basin 1 and 4** | Mean Difference | 1.77 | 1.73 | 1.76 |
| | p value | 0.13 | 0.06 | 0.13 |
| **Basin 2 and 3** | Mean Difference | 2.63 | 2.38 | 2.04 |
| | p value | 0.65 | 0.49 | 0.75 |
| **Basin 2 and 4** | Mean Difference | 2.59 | 2.29 | 2.27 |
| | p value | 0.13 | 0.07 | 0.17 |
| **Basin 1, 2, 3 and 4, 5** | Mean Difference | 1.44 | 1.31 | 1.29 |
| | p value | ***0.03*** | ***0.01*** | ***0.04*** |

The statistics do confirm the hypothesis, which is that there is a variation in storm surge heights between the Gulf Coast Region and the Atlantic Coast Region. Starting with comparisons between basins 1, 2 and 3, there is no significance. This is important to note, because basins 1, 2 and 3 are all within the Gulf Coast Region and there should be very little variation between averages for these areas. On the other hand, when basins 1, 2, and 3 were compared to basin 4, in the Atlantic Coast Region, the p values, although not significant by mathematical definition, do indicate there is a notable difference of averages between these areas.

After comparing averages from basin to basin, the averages of the entire Gulf Coast Region were compared to those of the Atlantic Coast regions. Final results do show a significant difference between surge heights for the Gulf Coast Region and the Atlantic Coast Region.

## Summary

Although data are sparse for this study, inferences can still be drawn that there is a greater storm surge in the Gulf of Mexico than the Atlantic. Referring to Figure 4.1, it does show that there is, especially in the Central Gulf Basin, a greater surge height in the Gulf Coast Region than the Atlantic Basin. In addition, p values, found in Table 4.11, show that there is significant height difference between regions. However, when looking at Figures 4.5 and 4.6, even though there is still a slightly higher surge in the Gulf, the increase in surge values with wind speed is linear, with nearly an identical slope, for the Gulf and Atlantic Regions. This might indicate that basins with a larger sample size show a higher surge, when in fact the same linear increase between surge height and wind speed applies to most locations.

# CHAPTER V

# CONCLUSIONS & DISCUSSION

## Conclusions

This study intended to show a variation in storm surge height between locations in the Atlantic Region and the Gulf Coast Regions, for like-category storms. Although surge heights varied in different regions, results conclude that category 2, 3 and 5 storms produce a significantly higher storm surge in the Gulf Coast Region than the Atlantic Region, whereas category 4 storms have a higher surge in the Atlantic region.

This study also found that the Atlantic Region experiences much less variation in storm surge heights between categories than the Gulf Coast Region. The Atlantic Region recorded its lowest surge value at almost 1.0 m with the highest surge height recorded at a little over 5.0 m, whereas the lowest surge value in the Gulf Region is just over 1.0 m and the highest surge value recorded is nearly 7.5 m. The variation in storm surge height in the Atlantic region is about 4.0 m, from category 2 to category 5 storms. In the Gulf Region there is a 6.5 m variation in surge heights from category 2—5 storms.

Understanding these surge variations and geographical features that enhance storm surge is very important not only for scientist, but for any persons living on or near the coast. Most coastal devastation from a hurricane is caused by storm surge (Hoover 1957) and it is generally accepted that hurricane strength and storm surge height are directly proportional (Coch 1994). The Saffir-Simpson scale categorizes storm strength based solely upon wind speed (Saffir 1977; Simpson and Riehl 1981), and results from this study suggest that the uni-variable Saffir-Simpson scale is not directly proportional to storm surge heights. The Saffir-Simpson hurricane scale reflects the strength of a hurricane over the ocean; however, the scale is less adequate in reflecting the effects of a hurricane on the coast at landfall because it does not take storm surge and other land-sea interactions into account (Bush 2001). Thus, this scale can be a false representation of potential storm surge heights, leading to underestimated predictions and projections of potential damage to an area.

Thus, it is important to understand the potential for damage due to storm surge, for a specific location, and not generalize potential storm damage strictly based upon a categorical ranking. With rapidly growing coastal regions, each hurricane that makes landfall has the potential for significant damage and destruction (Pielke and Landsea 1998). Although some of the costliest hurricanes have been category 4 or greater, this does not denote that storms of lesser strength should be considered less destructive.

## Discussion

After concluding this study, additional research into various areas of this thesis would be useful for future research.

1. As for data acquisition, having a detailed storm surge database would have made this study more efficient and possibly, it would have made the results more conclusive.
2. After examining the results of this study and finding that, in general, the storm surge heights are greater in the Gulf Coast Region, future research could look at

specific variables that might cause this to occur. Some of these variables could include, but are not limited to:

a. Angle of Attack: Find the angle at which a storm makes landfall and determine if this impacts surge height.
b. Storm origin: Was the storm genesis a tropical wave, Cape Verde storm, or was it a pre-existing storm system that intensified into a hurricane?
c. Intensity Track: Did the storm continually strengthen or did it strengthen, then weaken, then reintensify?
d. Location of Max Intensity: Did the storm intensify directly prior to landfall or did it intensify in the open waters? Does location of maximum intensity play a role how storm surge affected?

These questions or topics maybe helpful to further the examination into variables that affect or enhance storm surge.

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